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The fluvial evolution of the Holocene Nile Delta

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Abstract

The evolution of the Nile Delta, the largest delta system in the Mediterranean Sea, has both high palaeoenvironmental and archaeological significance. A dynamic model of the landscape evolution of this delta system is presented for the period c.8000–4500 cal BP. Analysis of sedimentary data and chronostratigraphic information contained within 1640 borehole records has allowed for a redefinition of the internal stratigraphy of the Holocene delta, and the construction of a four-dimensional landscape model for the delta's evolution through time. The mid-Holocene environmental evolution is characterised by a transition from an earlier set of spatially varied landscapes dominated by swampy marshland, to better-drained, more uniform floodplain environments. Archaeologically important Pleistocene outliers in the form of sandy hills protruding above the delta plain surface (known as “turtlebacks”), also became smaller as the delta plain continued to aggrade, while the shoreline and coastal zone prograded north. These changes were forced by a decrease in the rate of relative sea-level rise under high rates of sediment-supply. This dynamic environmental evolution needs to be integrated within any discussion of the contemporary developments in the social sphere, which culminated in the emergence of the Ancient Egyptian State c.5050 cal BP.

Keywords: Holocene, Palaeogeography, Middle East, Sedimentology, lakes, lagoons & swamps, Deltas, Nile, Geomorphology, fluvial

1. Introduction

The present Nile Delta is the latest in a long series of deltaic formations, probably going back to the Miocene (Said, 1981). A large amount of research has been undertaken on the Pleistocene and earlier history of the region, mainly as a result of oil exploration (Abu El-Ella, 1990; Rizzini et al., 1978; Said, 1981, 1971; Schlumberger, 1995), but the Holocene landscape evolution of the area remains quite poorly understood in comparison with the rest of the Nile system. In the upper catchment of the White Nile (Cockerton et al., 2015), Blue Nile (Marshall et al., 2011), at the Nile confluence (Williams et al., 2015) and especially through the Egypt-Sudan desert reach (Honegger and Williams, 2015; Macklin et al., 2013; Vermeersch and Van Neer, 2015; Woodward et al., 2015, 2001), much recent work has reported on Holocene landscape succession, relationships between the changing landscape, human settlement and culture, and the varying roles of climatic and other drivers of change in effecting these changes.

It is only the Holocene evolution of the delta's coastal margin that is understood to a level comparable with the rest of the Nile system (Stanley and Warne, 1993a). The evolution of the extensive fluvial plain (approx. 15,000km²) is less-well known, despite a number of attempts at a delta-wide synthesis over the last century (Bietak, 1975; Butzer, 2002, 1976, 1974; Fourtau, 1915; Hassan, 1997; Said, 1992;

Sandford and Arkell, 1939; Stanley and Warne, 1993a,b). This is surprising, given the region's importance in the formative period of the world's first nation state of Ancient Egypt, and its modern-day importance for the nation of Egypt, containing half of the country's agricultural land and population. A better understanding of the mid-Holocene evolution of this area, south of the zone dominated by coastal processes – is urgently needed.

The most recent landscape synthesis of this region (Butzer, 2002) relied solely on lithostratigraphic and chronostratigraphic data collected prior to 1991. Since that time, and especially over the past ten years, numerous teams have carried out geological and geoarchaeological research in the delta, providing a wealth of data on the development of the landscape, none of which has ever been integrated into a delta-wide Holocene landscape synthesis.

This paper incorporates this recent and ongoing research to provide a new and updated perspective on the evolving mid-Holocene landscapes of the delta, a perspective which needs to be integrated into discussions of the emergence of the ancient Egyptian state, and other sociocultural and economic history studies of the region over the *longue durée*. The vast deltaic plain was the breadbasket of the Ancient Egyptian state, containing the largest amount of cultivateable land in the country, but without a detailed palaeoenvironmental model it cannot be truly

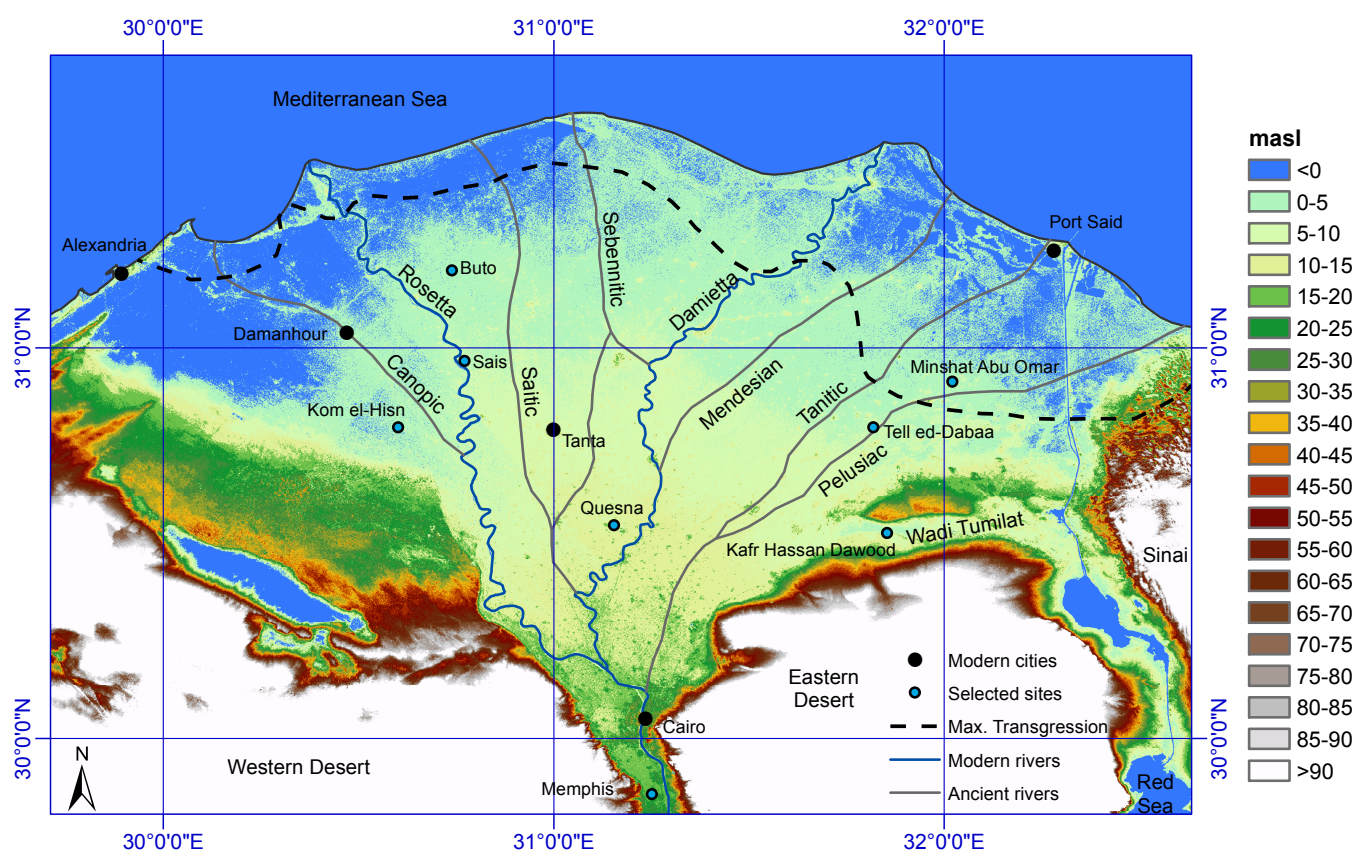


Figure 1: Map of the Nile Delta (SRTM data). The locations of ancient river branches are after Bietak (1975); Butzer (2002); the extent of maximum transgression is as given by Stanley and Warne (1993a). Selected archaeological sites are also shown.

integrated into a geoarchaeological synthesis (Clarke et al., 2016; Hassan, 2010, 2009; Macklin and Lewin, 2015).

The paper focusses on the time period c. 8000 to 4500 cal BP, as this covers the period of greatest geomorphological change, during which sea-level was approaching its modern-day position (Fleming et al., 1998), and the modern Nile hydroclimatic system was being established, as the “African Humid Period” gave way to more arid conditions (Shanahan et al., 2015). This is also a time period without substantial human factors contributing to and complicating the remodelling of the deltaic landscapes, but is an episode crucial for understanding the palaeoenvironmental context of Ancient Egyptian State Formation.

1.1. Regional setting

The Nile Delta is an alluvial plain in the north of Egypt (Fig. 1) constituting by far the largest continuous expanse of agricultural land in the country. Bounded by desert to both the east and west, its apex is at Cairo, where the river divides into two main distributaries: the Rosetta and Damietta, which discharge over the triangular-shaped alluvial plain and flow north into the Mediterranean. Many more distributaries existed in prior time periods (Butzer, 2002; Hassan, 1997), and the apex of the network was also further south (Bunbury, 2013; Lutley and Bunbury, 2008).

The geology of the alluvial plain is relatively simple. The Holocene deposits are mainly represented by a thin veneer of silty sediments of the Bilqas Formation, which lie unconformably on top of the thick, sandy Mit Ghamr Formation (Rizzini et al., 1978), whose top surface comprises the erosion remnant of a buried alluvial landscape formed under a different hydrological regime (Adamson et al., 1980; Stanley and Warne, 1993a). Some of these remnants protrude above the modern delta surface as sandy hills, known as “turtlebacks”, or “gezira” (Judd, 1897).

The plain is densely populated and farmed such that little natural vegetation remains. Almost all the water influx to the region is provided by the river Nile. This river displays pronounced seasonality, related to the differing catchments of its three main tributaries. The Blue Nile and Atbara drain the Ethiopian Highlands and provide the majority of the Nile’s annual discharge and sediment flux during the Nile flood between July and October, while the White Nile drains Central Africa, provides minor year round discharge but only accounts for 3% of the sediment flux (Woodward et al., 2015). Since the damming of the river at Aswan the Nile through Egypt has not flooded.

2. Towards a unified model for mid-Holocene fluvio-deltaic evolution

The Nile Delta developed during a period of decreasing rates of sea-level rise and high sediment supply within the mid-Holocene. Initially, high rates of relative sea-level rise stimulated high rates of floodbasin aggradation, and gave

rise to the associated development of a swampy, wetland landscape dominated by the formation of crevasse splays (Fig. 2). High rates of base-level rise would have resulted initially in a reduction of the river gradient, causing a corresponding decrease in energy to transport sediment, and elevated in-channel aggradation rates. These high rates of in-channel aggradation would have in turn led to channel superelevation, since to maintain constant volumetric flow the channels would have built their margins above the surrounding floodplain (Jerolmack and Mohrig, 2007; Mohrig et al., 2000). Superelevation in turn would have led to widespread crevassing, frequent avulsion, and high rates of floodplain aggradation (Aslan et al., 2005; Jerolmack, 2009; Kraus, 1996; Kraus and Aslan, 1993; Phillips, 2011; Mohrig et al., 2000; Slingerland and Smith, 2004). Rapid floodplain aggradation then inhibited soil formation and resulted in the development of a wetland landscape (Smith and Pérez-Arlucea, 1994; Smith et al., 1989; Willis and Behrensmeyer, 1994). The resulting typical environment (Fig. 2) has been referred to as “Large-Scale Crevassing”, or “LSC” (Pennington et al., 2016; Törnqvist, 1993).

Following the mid-Holocene transition to lower rates of relative sea-level rise, lower in-channel aggradation rates would have meant that crevassing and avulsion became relatively less dominant processes of landscape formation, and rivers would have migrated across their floodplain primarily via lateral channel migration and point bar deposition (Brown, 1997; Jerolmack, 2009; Jerolmack and Mohrig, 2007; Pennington et al., 2016). This process would have “swept-up” other channels and so tended to establish a simplified, reduced channel network. With less crevassing, floodplain aggradation rates would have decreased, and soils would have developed. The resulting landscape (Fig. 3) has been referred to as a “Meandering” deltaic environment (Pennington et al., 2016). A summary of the differences between the “LSC” and “Meandering” environments is given in Table 1.

Ultimately, it is the relationship between the rate of vertical aggradation (dominant in LSC) and the rate of lateral migration (dominant in the “Meandering” landscape) that is the main determinant of the character of the landscape. If vertical aggradation is dominant over lateral migration, channel superelevation will occur, leading to the LSC landscape; if lateral migration is dominant this will not be the case. The Mobility Number (M) (Jerolmack and Mohrig, 2007), is a dimensionless number that encapsulates this ratio. It is defined (equation 1) as the ratio between the time required for a river to vertically aggrade one-channel height, and the time required for a river to migrate one channel width, and thus expresses whether a river predominantly aggrades vertically or migrates laterally.

$$M = \frac{hV_c}{BV_a} \quad (1)$$

In this equation, h is the river depth at bankfull discharge, B the width, V_c the bank erosion rate and V_a the

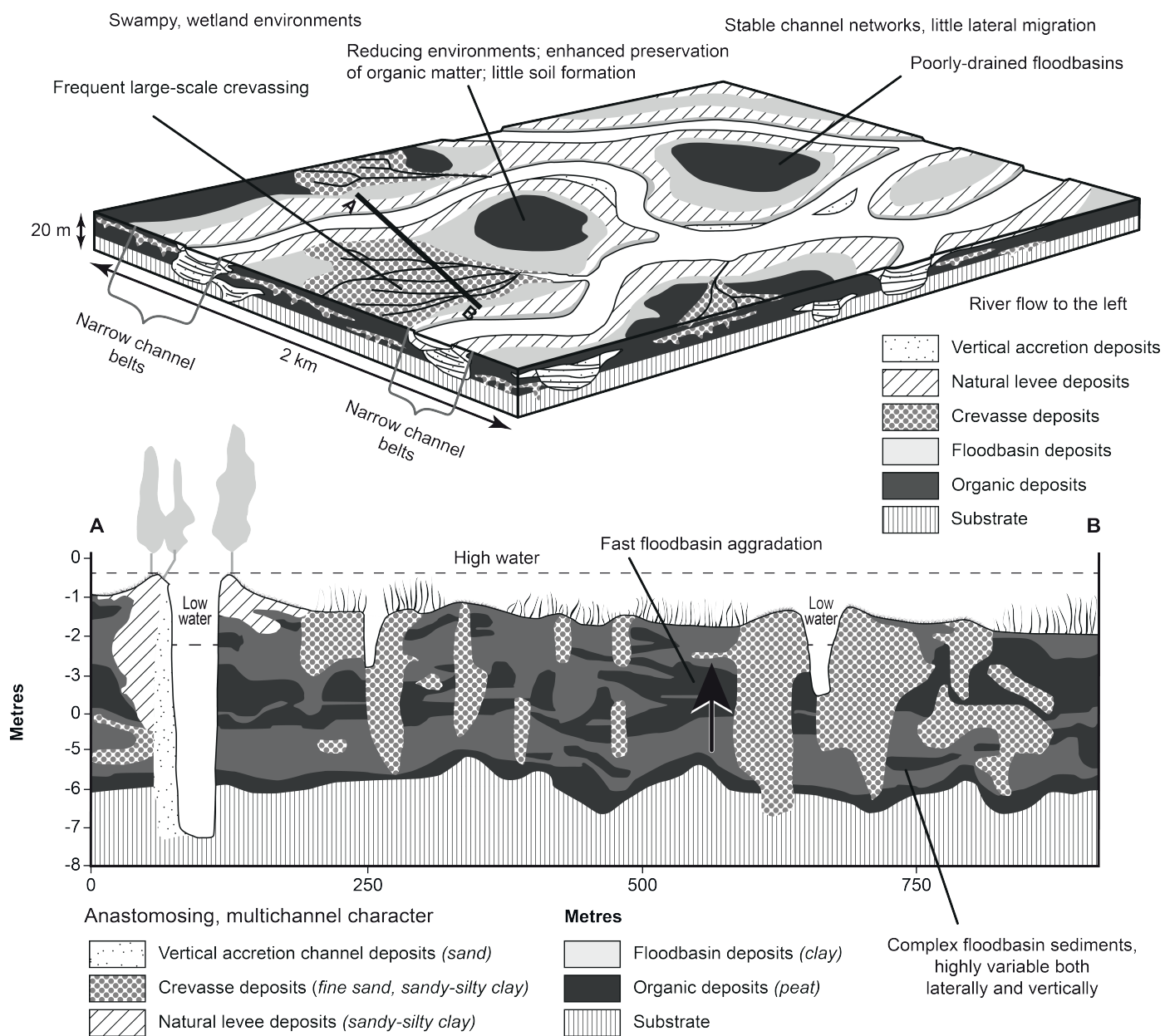


Figure 2: The LSC landscape of the early mid-Holocene, in equilibrium with high rates of sea-level rise. Modified after Weerts (1996).

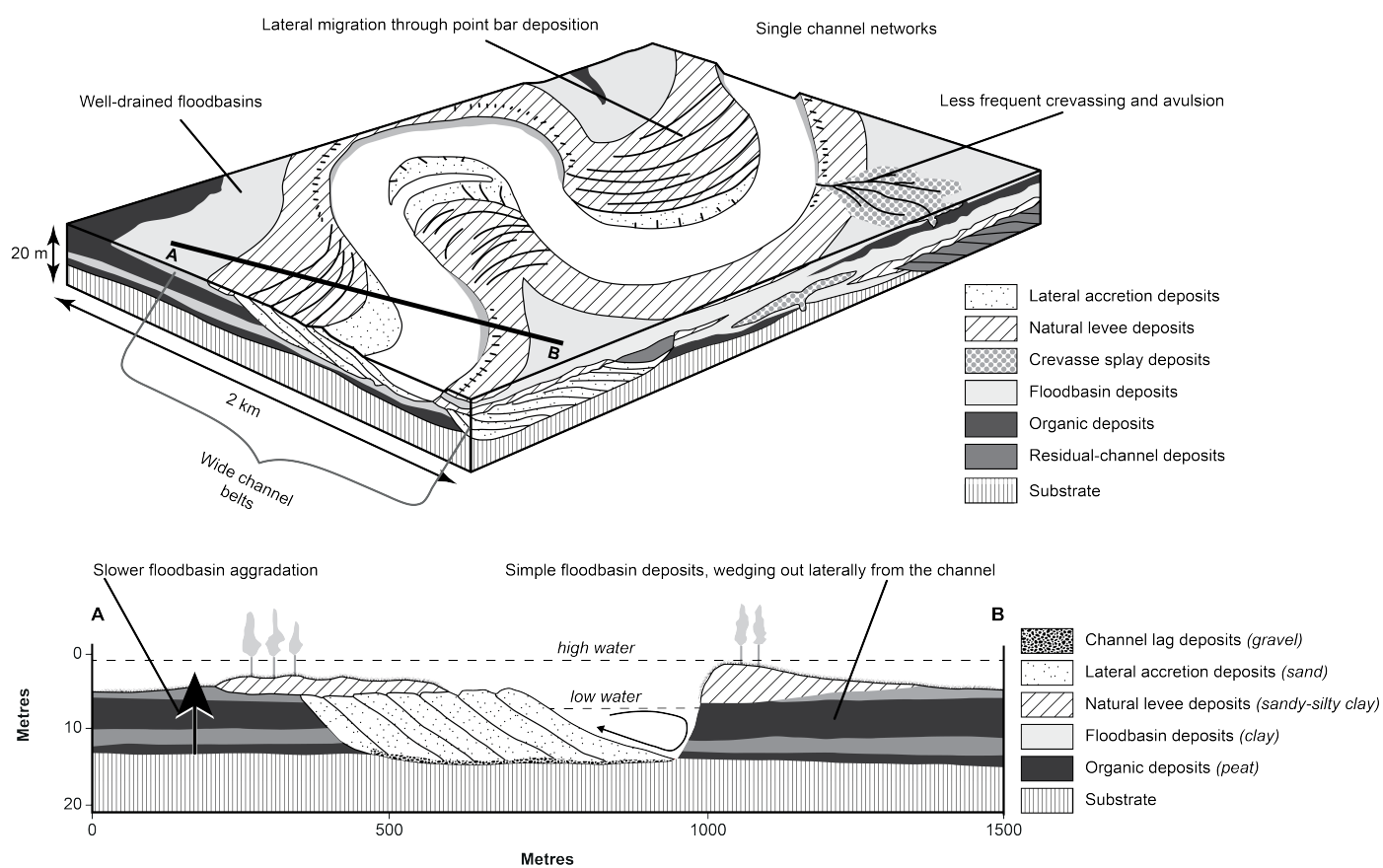


Figure 3: The “Meandering” landscape of the later mid-Holocene, in equilibrium with lower rates of sea-level rise. Modified after Weerts (1996).

in-channel vertical aggradation rate. Rivers with values of $M > 10$ are characterised as “single-channel”, those $M < 1$ are “anastomosing” (Jerolmack, 2009). The LSC facies is thus the result of lower M driven by higher V_a during the early Holocene, and the LSC-Meandering Transition was a result of an increase in M driven by lower V_a during the later Holocene. The driving reduction in V_a was forced primarily by decreasing rates of base-level rise, although it could have been further driven by changes in discharge and sediment-supply (see section 7) by analogy with similar shifts in riverine dynamics elsewhere (Macklin et al., 2015, 2013; Woodward et al., 2001).

3. Previous work on the Holocene landscapes of the delta

3.1. Landscape evolution of the coastal zone

The evolution of the Nile Delta’s coastal region, although not the focus of the current study, is fairly well understood (Fig. 4) as a result of research carried out by the Smithsonian Institution’s Mediterranean Basin (MED-IBA) survey in the 1980s and 1990s. Building on previous work in the coastal area (Attia, 1954; Sestini, 1976; Sneh et al., 1986), this project drilled 87 radiocarbon-dated cores within the coastal fringe of the delta (Stanley et al., 1996). This work has been built upon by more recent studies of the Holocene sequence (Flaux, 2012; Flaux et al., 2017, 2013, 2011; Marriner et al., 2013, 2012b; Moshier and El-Kalani, 2008) as well as geoarchaeological investigations at specific archaeological sites (Ghazala et al., 2005; Wilson, 2011, 2010; Wilson and Grigoropoulos, 2009).

The general sedimentary sequence in the coastal region is presented in Fig. 5. At the base are Late Pleistocene iron-stained quartz-rich sands and stiff muds (“Sequence I Deposits”). Unconformably above this unit lies quartz-rich sands with a shallow marine fauna (“Sequence II Deposits”, or “transgressive sands”), then another depositional hiatus and a variety of lithologies which together comprise “Sequence III Deposits”.

The predominantly sandy “Sequence I Deposits” at the base represent terrestrial sedimentation on a partially vegetated braided river-plain (Stanley and Warne, 1993a). These deposits are dated to c.38,000–12,000 cal BP (Butzer, 2002), a time when the coastline was located significantly further north of its current position (Summerhayes et al., 1978). They are correlated regionally as the Mit Ghamr Formation.

The overlying “Sequence II deposits” record the mid-Holocene transgression, and date from prior to c.8000 cal BP (Stanley and Warne, 1993a). The spatial distribution of the unit thus approximates the extent of the transgression, which was more extensive in the east than the west (Fig. 4).

Finally, the variety of lithologies represented by the deposits of “Sequence III” date from c.7500 cal BP onwards. These sediments record a range of marine, semiter-

restrial, coastal, estuarine, lagoonal and in some cases fluvial deltaic environments.

3.2. Available lithostratigraphic and chronostratigraphic data from the fluvial zone

The evolution of the fluvially-dominated region of the Nile Delta is less well-understood than the coastal fringe, although this is not necessarily due to a lack of primary data. There are a large number of boreholes known from the region $> 3\text{m}$ deep (Fig. 6), many of which have been carried out since 1991 and were not included in the most recent synthesis of the delta’s evolution (Butzer, 2002). Some of these cores have been drilled and published within a geological framework, but many others have been carried out as part of archaeological research in the area. Isolated studies have also been undertaken and published from within the disciplines of hydrology and engineering. The supplementary information contains a list of all the surveys and cores from the fluvial zone that were assessed as part of the current synthesis (1640 borehole records).

4. Methods

In order to create an overall palaeogeographic reconstruction of the delta through time, it was necessary to a) collate and rectify all available lithostratigraphic and chronostratigraphic data from the region; b) revise the stratigraphic framework; c) model the geological data in 3D through time.

4.1. Database compilation and stratigraphic revision

A survey of the published literature as well as ongoing fieldwork by the authors provided 1640 relevant core records within the fluvial zone of the delta. Study of these cores allowed for a redefinition of the delta’s Late Pleistocene and Holocene stratigraphy (section 5), and the records were input to a stratigraphic database (provided in the supplementary information). The available geological information that can be ascertained from these records is of varying quality, and is usually limited to basic sedimentological descriptions. A lack of research focus, coupled with (and partly as a result of) export restrictions have meant that there are few published LOI, magnetic susceptibility or heavy-mineral records, and no published cores from this fluvial region have been studied with XRF techniques, nor with stable isotope analysis.

Most boreholes from the coastal zone of the delta were not input to the database, as palaeogeographic constructions based on these cores are already readily available; the only boreholes which were included from this zone were those of the MEDIBA survey, incorporated only to provide the regional variability in the underlying Mit Ghamr Formation (Marriner et al., 2012b). Neither were cores around the delta apex, due to concerns over local effects.

A complication with the elevations of the borehole records is that they were not all presented with reference to the

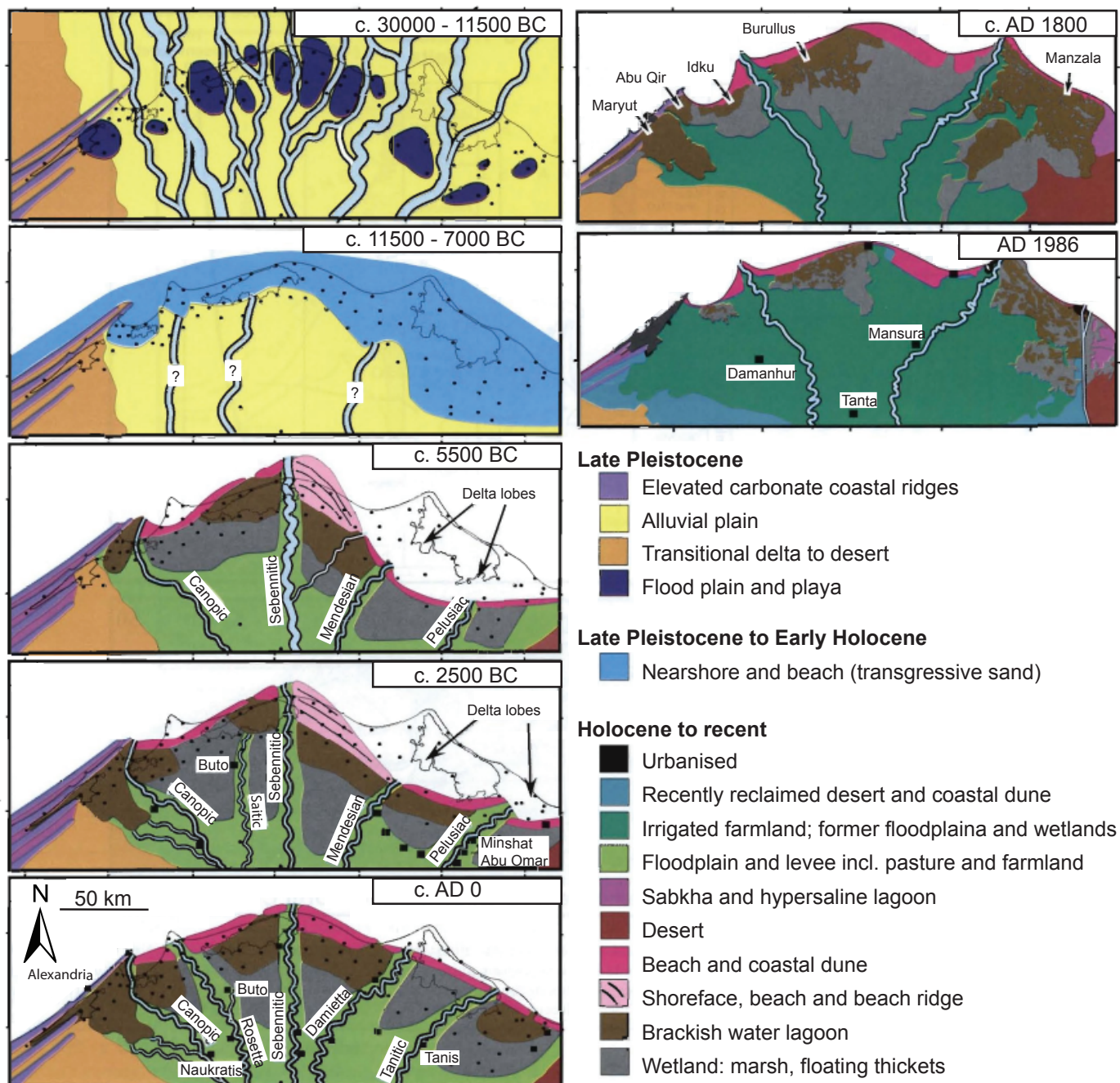


Figure 4: Environmental history of the Nile Delta margin, according to the MEDIBA survey. After Stanley and Warne (1998)

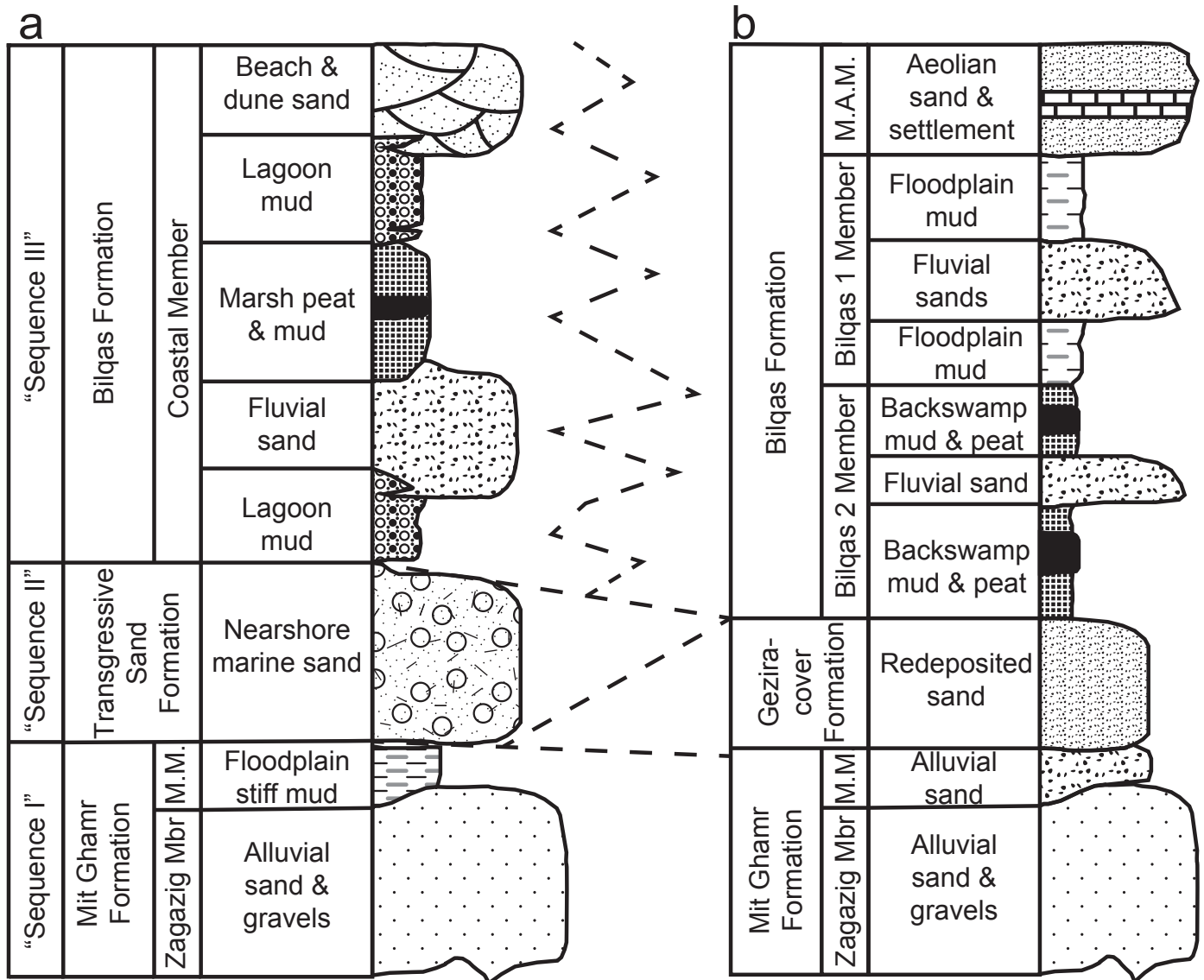


Figure 5: Representative logs through the a) coastal and b) fluvial zones of the Nile Delta. M.A.M. = Modern Aeolian Member; M.M. = Minuf Member.

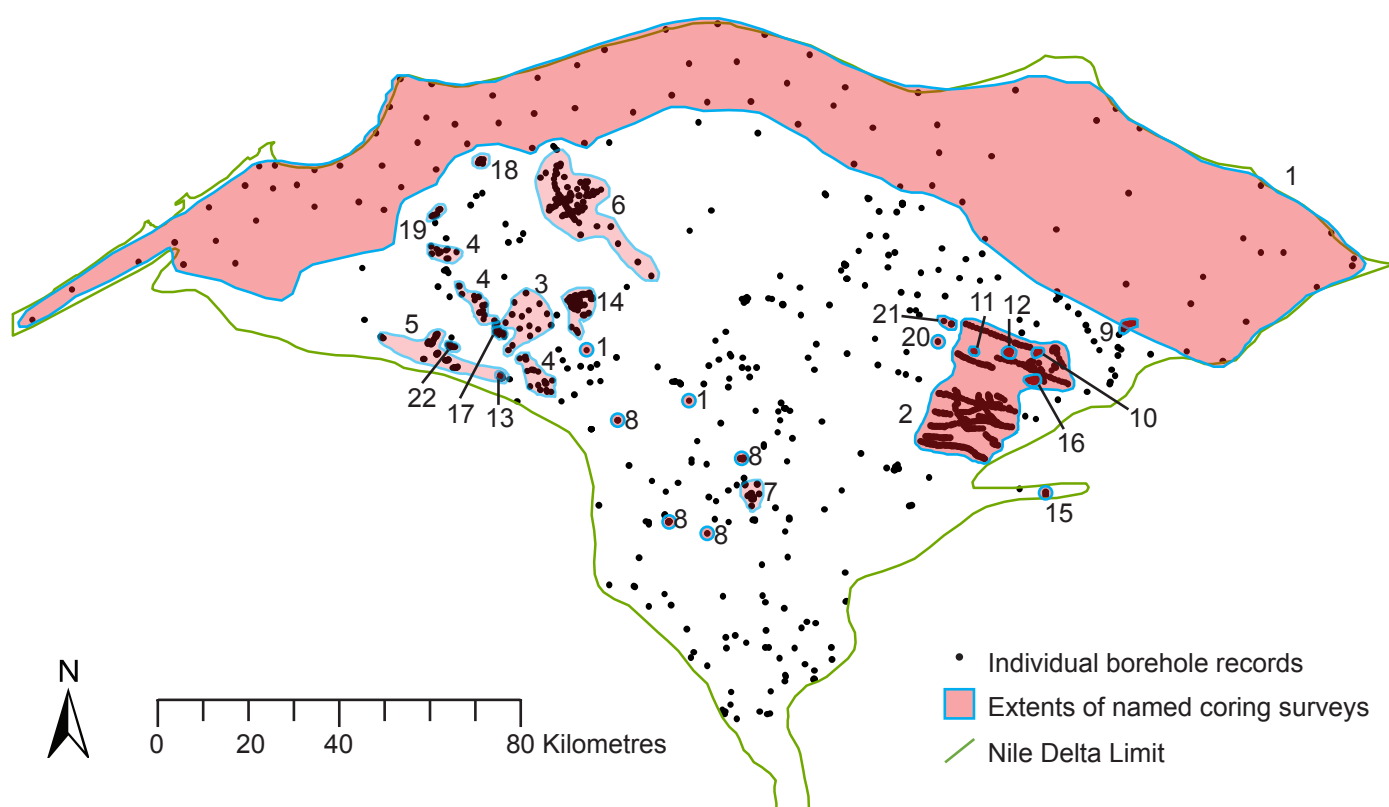


Figure 6: Locations of cores undertaken in the Nile Delta and whose records are available for consultation. Labelled regions represent particular surveys as follows: 1) MEDIBA and other surveys in the coastal zone (not all cores shown); 2) AUSE (Amsterdam University Survey Expedition to the Nile Delta); 3) MUWDS (Mansoura University Western Delta Survey); 4) WDRS (West Nile Delta Regional Survey); 5) WDLP (Western Delta Landscape Project); 6) BRS (Buto Regional Survey); 7) Quesna; 8) Other cores of the MAS (Minufiyeh Archaeological Survey); 9) Minshat Abu Omar; 10) Tell Ibrahim Awad; 11) Tell Gherier; 12) Tell el-Iswid S; 13) Kom el-Hisn; 14) Sais; 15) Kafr Hassan Dawood; 16) Tell ed-Dab^a; 17) Kom Geif; 18) Tell Mutubis; 19) Kom al-Ahmer/Kom Wasit; 20) Tell el-Farkha; 21) Kom el-Khilgan/Tell es-Samara; 22) Kom Firin. Most of the other cores shown were published by the Survey of Egypt.

Table 1: Summary of differences between the LSC and “Meandering” fluvial environments.

Geomorphological characteristic	LSC	Meandering
In-channel aggradation rates	High	Low
Floodplain aggradation rates	High	Low
Channel migration	Little	Substantial
Network	Multichannel	Single-channel
Alluvial architecture	Narrow sandbodies	Tabular sandbodies
Avulsion	Frequent	Less frequent
Flooding style	Crevassing	Overtopping
Environment	Poorly-drained swamps	Well-drained floodplains
Floodbasin sediments	Complex, varying substantially both laterally and vertically	Simpler, wedging out laterally from the channel

same datum. Most core heights were recorded with reference to the Survey of Egypt datum, which approximates the true geoid more exactly than any other (Dawod and Ismail, 2005), but a small number of cores were expressed relative to EGM2008 (Pavlis et al., 2012). Furthermore, where no elevations above sea-level were given in the borehole records, approximate heights above sea-level were inferred using SRTM data (Jarvis et al., 2008), which expresses heights relative to the EGM96 geoid (Lemoine et al., 1998). It was necessary to transform the elevations of each core which referenced EGM96 and EGM2008 in order to express them relative to the same datum (see supplementary information). The corrections applied by this procedure are significant (up to several metres)

A similar survey of the available literature further reveals 96 stratified radiocarbon, OSL and other dates from within “natural” sedimentary deposits in the fluvial region of the Nile Delta, which were input to a separate chronostratigraphic database (supplementary information). Very few coring surveys collected samples for radiocarbon or other scientific dating, mainly due to restrictions on the export of such material from Egypt. Other projects have used very well-correlated sedimentary horizons of identifiable pottery as a (relative) chronostratigraphic marker. Of these 96 dates, 71 were useful for estimating the aggradation history of the floodplain. Others were sourced from within very organic-rich deposits which data suggest have undergone substantial compaction, or were from non-floodplain units. No age-depth information was included in this database from the coastal zone, due to the hypothesised presence of a tectonic hinge-line, north of which the subsidence history is not representative of that further south (Stanley and Warne, 1998).

4.2. Geological palaeolandscape and aggradational modelling

In order to create a four-dimensional landscape model for the Holocene evolution of the Nile Delta, the changing spatial extents of the main sedimentary facies and the aggradation history of the delta floodplain had to be established. The changing spatial extents of the different environments in the fluvial zone were mapped through an in-depth analysis of the chronostratigraphic data (sup-

plementary information), by considering the sedimentary units in which each date was hosted. In the coastal zone, the changing environments were copied from previous syntheses that had summarised the work in this region (Stanley and Warne, 1998, 1993a).

The aggradation history of the fluvial sediments was then calculated, which allowed for the mapping of the locations and palaeotopography of the turtlebacks through time. First, minimum-depth geological surfaces of the top surface of each stratigraphic unit were created, using a Kriging algorithm (details in supplementary information). This provided a map of the variable height of the “pre-delta” topography upon which the Holocene delta was laid down (Fig. 7). Then, the spatially and temporally variable aggradation history of the deposits above was established by modelling the data within the chronostratigraphic database. An age-depth diagram for all floodplain sediments of the Bilqas Formation in the fluvial zone of the delta was created (Fig. 8), as well as a series of regionally-specific age-depth diagrams (Fig. 9). The temporal imprecision in these figures was used to create a range of different aggradation models of the Bilqas Formation, the most appropriate of which was selected by using the modelled top surface of the Bilqas 2 Member as an independent estimate of the aggrading height of the floodplain at the time that Bilqas 2 deposition gave way to Bilqas 1 deposits in any particular location.

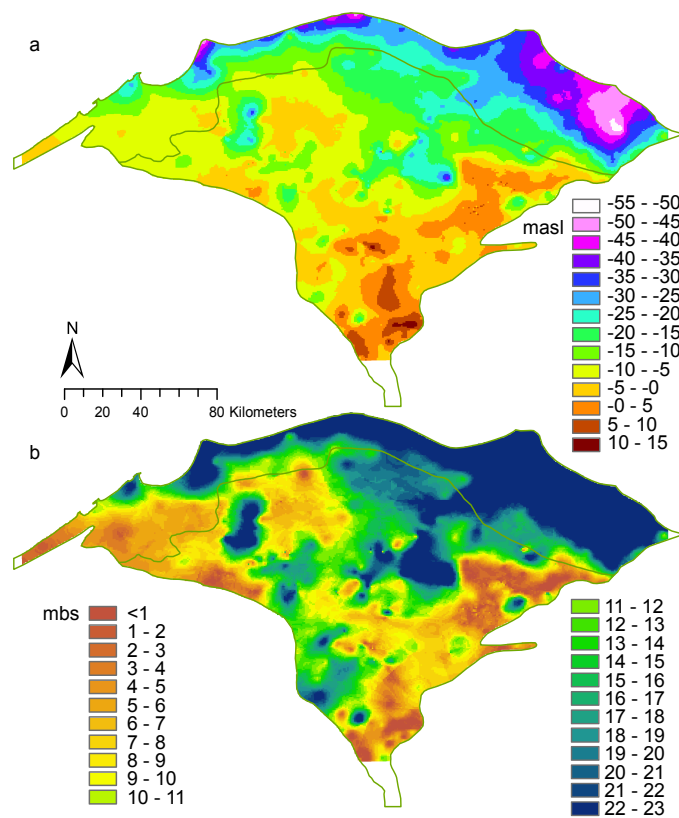


Figure 7: “Pre-Delta” topographic surface of the combined Mit Ghamr and Geziracover Formations a) in metres above sea level. b) in metres below modern delta surface.

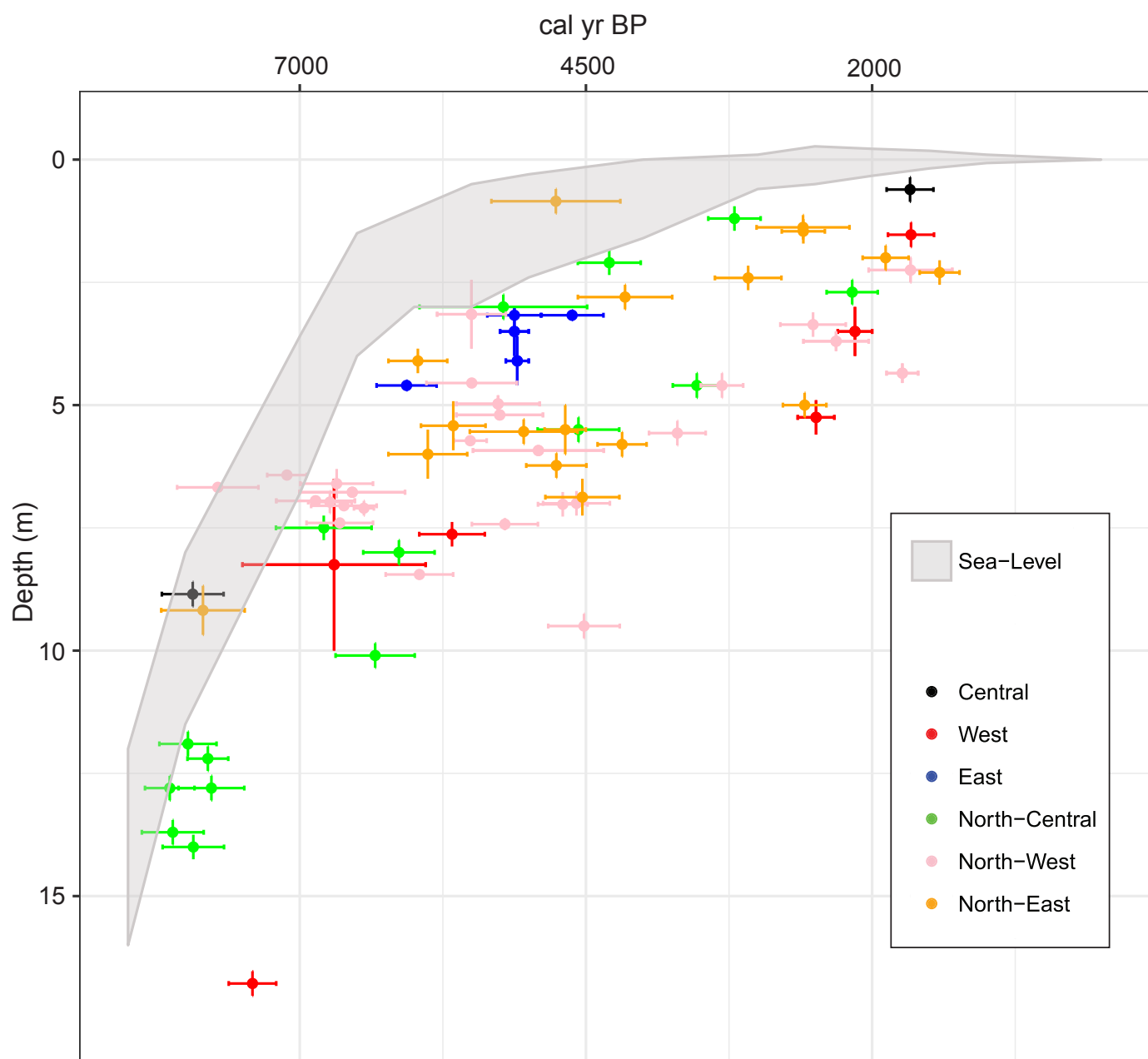


Figure 8: Age-depth model of stratified dates within the fluvial Nile Delta. Error bars represent 95% probability windows; the shaded region is the sea-level curve for Israel (Sivan et al., 2004, 2001); no more reliable Holocene sea-level curves exist specifically for Egypt.

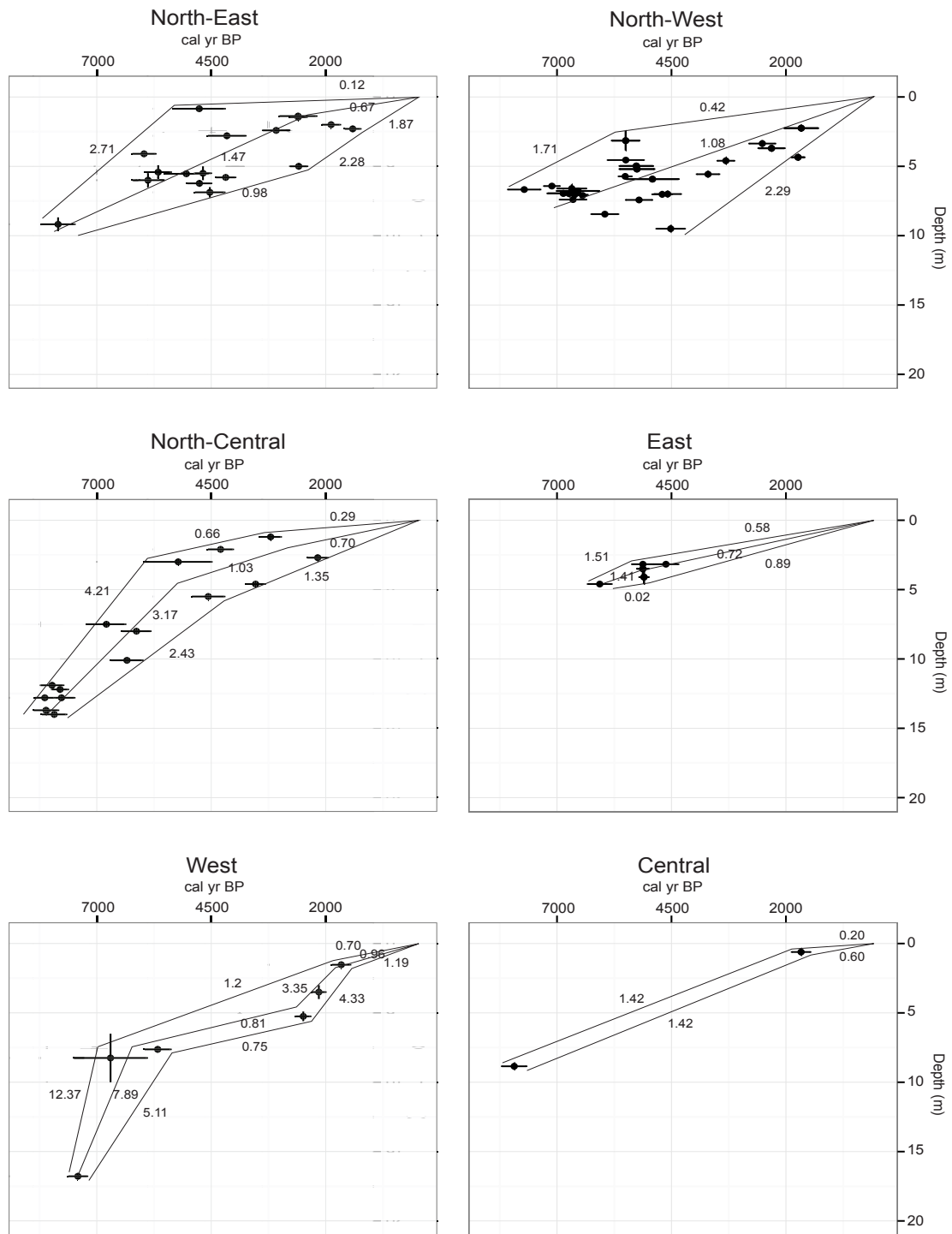


Figure 9: Age-depth models for the six different regions of data for the fluvial Nile Delta. Three sets of line segments are shown for each panel; the uppermost in each case represents the fastest aggradational history, the middle an average aggradational history and the lower the slowest aggradational history supported by the data. Numbers refer to aggradation rates for each line segment in mm/yr.

5. A new stratigraphic framework for the Holocene Nile Delta

A new stratigraphic framework is proposed for the deposits of the Nile Delta, which reflects the overall environmental evolution of the area through the Holocene. Eight stratigraphic units within four Formations are defined, displayed in Table 2 and on Fig. 5. The most important conceptual contribution of the present synthesis is that it divides the mid- and late Holocene fluvial sediments of the delta plain into two Members: Bilqas 2 and Bilqas 1, representing the LSC and “Meandering” environments respectively. Standard geological naming conventions are followed for the Pleistocene units. The Holocene units are named after the facies they represent, except where a previous name already exists (Bilqas).

In no location are all eight units seen in the same core. The Transgressive Sand Formation and Coastal Member are localised to the northern margin of the delta, while the Modern Aeolian Member and Geziracover Formation appear only in certain localities. Fig. 10 shows in which cores each unit was encountered. The results of previous surveys have been reinterpreted within this new stratigraphic framework (Fig. 11), and are discussed below.

5.1. The Mit Ghamr Formation

The Mit Ghamr Formation (Rizzini et al., 1978) mainly comprises medium-coarse quartzose sands, containing pebbles

of quartzite, chert and dolomite (Rizzini et al., 1978), some autigenic carbonate nodules (El-Awady, 2009), rare gastropod shells (Buck, 1990, p. 80), as well as some finer layers. It can, however, be separated into two different units, with the lowermost unit (renamed here as the Zagazig Member) coarser and mineralogically different to the upper unit (renamed as the Minuf Member). The top of the unit is very uneven, and often made up of a calcareous white palaeosol some 10–40cm thick (Hamdan, 2003). In other locations the top appears altered in colour to greenish-grey as a result of a reduced iron coating on the sand grains (Andres and Wunderlich, 1991). It is this unit that usually forms turtlebacks where its top surface rises above the modern-day floodplain surface (Butzer, 1959; Fourtau, 1915; Judd, 1897; Kholief et al., 1969; Said, 1981).

5.1.1. Zagazig Member:

The Zagazig Member has been previously known by other names: the “sub-delta formation” (Judd, 1897) or the “Lower Buried Channel” (Sandford and Arkell, 1939). It has also been described as a unit composed of “coarse and fine sands interfingering with pebbly or gravelly beds” (Fourtau, 1915); “several generations of Pleistocene sands and gravels” (Butzer, 1974); or “Mid-Pleistocene coarse sands/cobble gravels” (Butzer, 2002). These sands also usually correspond to the “diluvial deposits” noted by the Survey of Egypt (Attia, 1954).

The material is generally of a grade between $\phi=2.5$ and $\phi=-5$, with a skew to the finer grain sizes (Andres and Wunderlich, 1991; Buck, 1990; Kholief et al., 1969; Rowland and Hamdan, 2012), and is thus often a medium sand with isolated larger clasts, although in some locations may be significantly coarser (Attia, 1954). It is broadly yellow in colour (Buck, 1990; El-Shahat et al., 2005; de Wit and van Stralen, 1988b; Hamdan, 2003; Hamroush, 1987; Kholief et al., 1969; Rowland and Hamdan, 2012). The sediments are moderately-to-poorly-sorted, quite homogeneous, and sometimes laminated or cross-stratified with evidence of fining-upwards cycles (Hamroush, 1987; Kholief et al., 1969; Rowland and Hamdan, 2012). The sands are predominantly quartz (80–100%), with some plagioclase feldspar (Zaghloul et al., 1980). The grains themselves have very thin coatings of iron oxide and sometimes carbonate (El-Shahat et al., 1999; Kholief et al., 1969; Stanley and Chen, 1991). Other minerals include iron oxides (magnetite, haematite and ilmenite), hornblende, augite and epidote (El-Hinnawi and El-Shahat, 1969; El-Shahat et al., 2005; Hamdan, 2003; Kholief et al., 1969; Zaghloul et al., 1980). The name given to the unit here comes from the location of the borehole in which it was first recognised (Judd, 1897). The sands are generally correlated with the Qena Prenile sands of Upper Egypt (Said, 1981, p. 56), as well as the Sath Ghorab Formation (Hamdan, 2003).

5.1.2. Minuf Member:

Lying unconformably above the Zagazig Member is another unit within the Mit Ghamr Formation: the Minuf

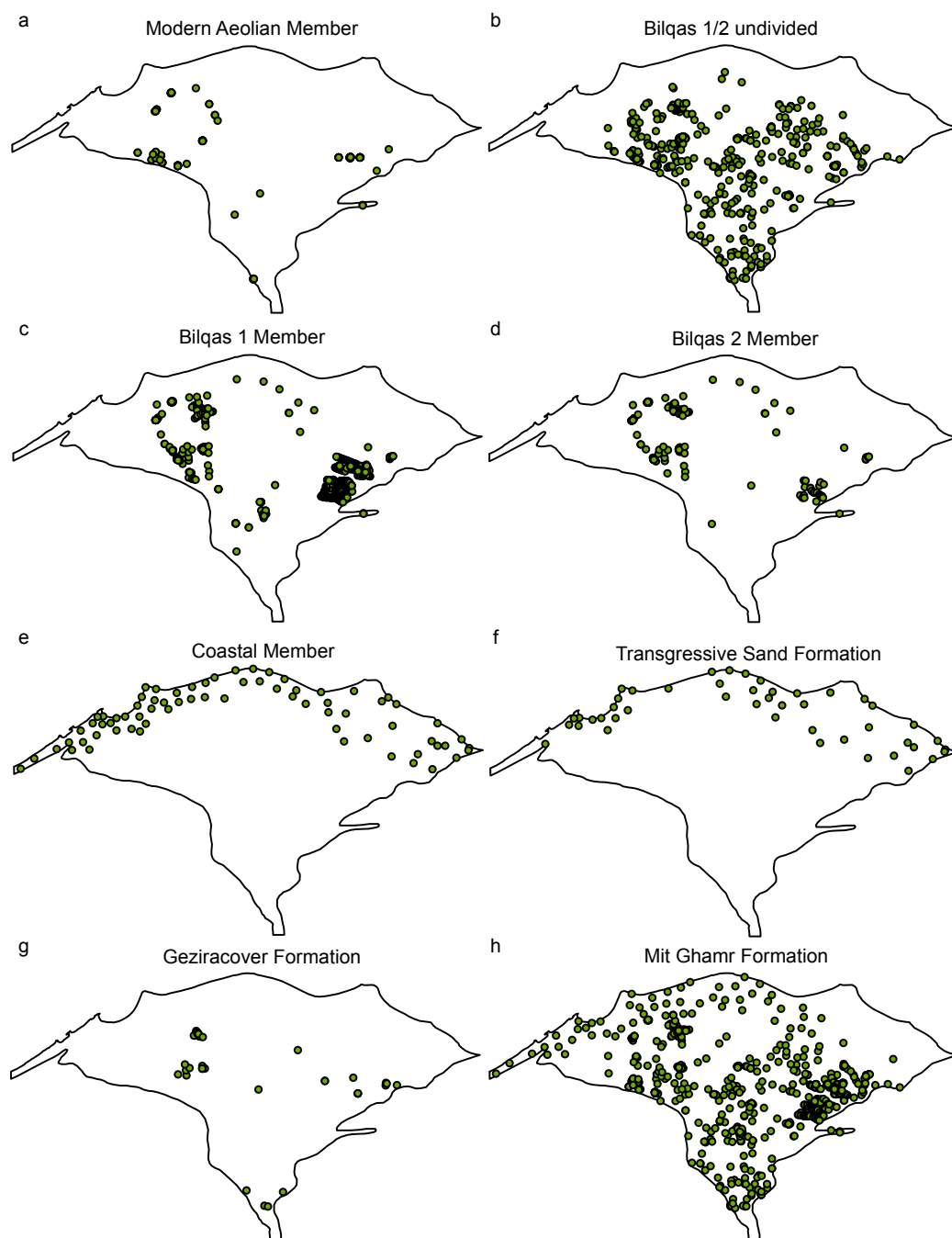


Figure 10: Maps showing the distributions of cores containing each unit.

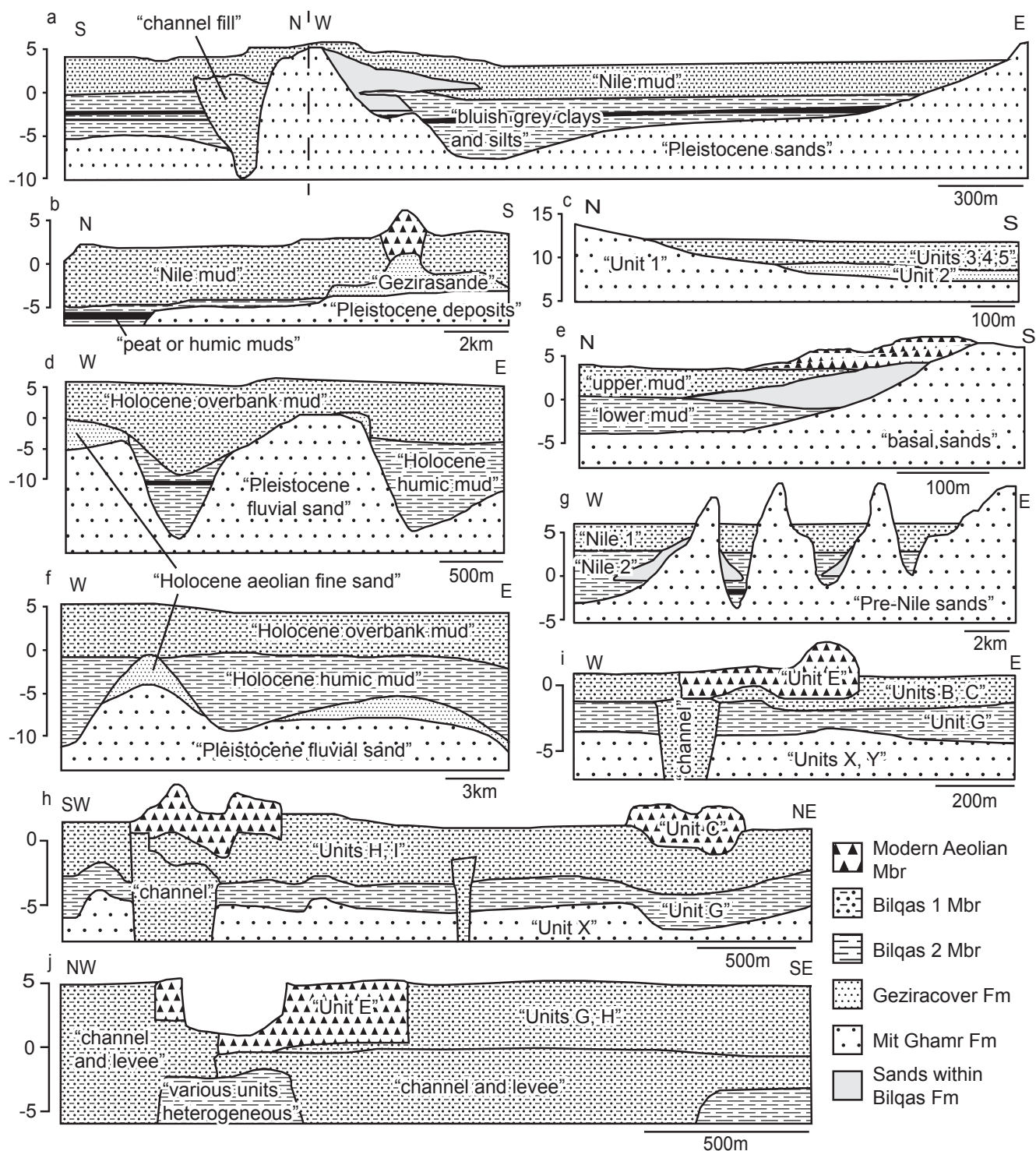


Figure 11: Summary cross-sections of previous localised geoarchaeological/geological surveys in the Nile Delta, reinterpreted within the stratigraphic divisions of the current synthesis. a) Minshat Abu Omar, adapted from Andres and Wunderlich (1992); b) Buto Regional Survey, adapted from Hamdan (2003); c) Quesna, adapted from Rowland and Hamdan (2012); d) Sais, adapted from El-Shahat et al. (2005); e) Kafr Hassan Dawood, adapted from Hamdan (2003); f) The Mansoura University Western Delta Survey, adapted from El-Awady (2009). g) The Eastern Delta region of the Amsterdam University Survey Expedition project, adapted from Andres and Wunderlich (1992); h) Kom al-Ahmer/Kom Wasit; i) Tell Mutubis; j) Kom Geif. The names of the units given in quotation marks are those from the published literature; the key shows their reinterpretation within the framework of the current synthesis.

Table 2: New stratigraphic framework for Recent Nile Delta deposits. Dashed lines indicate unconformity surfaces; those units in *italics* are new to the current synthesis.

<i>Modern Aeolian Member</i>	Bilqas Formation
<i>Bilqas 1 Member</i>	
<i>Bilqas 2 Member</i>	
<i>Coastal Member</i>	

Transgressive Sand Formation	
<i>Geziracover Formation</i>	

<i>Minuf Member</i>	Mit Ghamr Formation
<i>Zagazig Member</i>	

Member. Although these deposits have been known about for many years as a combination of the “Upper Buried Channel” and “hornblende sands and silts” (Sandford and Arkell, 1939), and together under the name “Fine Nilotic Sands” (Butzer, 1974), they have generally eluded systematic description and correlation with other units in Egypt, and are not discussed at any length in geological syntheses (Said, 1993, 1981; Tawadros, 2011).

The sands within the unit differ from the underlying Zagazig Member by the presence of mica, their less massive character and finer grain size, and their hosting of stiff or compact clayey lenses (Butzer, 2002, 1974; Sandford and Arkell, 1939). These lenses probably originated in fragmented Late Pleistocene floodbasins, especially near the modern-day coastline (Butzer, 2002; Chen and Stanley, 1993). Based on radiocarbon dates of the MEDIBA survey and the BRS, the deposits appear to have been laid down between c.28,000 and 11,000 cal BP (Butzer, 2002). They most probably comprise a complex set of numerous different minor units of different genetic origin, probably spanning a large age-range (Butzer, 2002), deposited under an earlier, braided Nilotic regime (Adamson et al., 1980). The name given to the unit here is chosen after the location of one of the first boreholes in which the unit was recognised (Fourtau, 1915).

5.2. The Geziracover Formation

In a small number of locations, lying unconformably and directly atop the Mit Ghamr Formation are deposits which have been interpreted as primarily aeolian reworking of the sands beneath. These are observed, for instance, at Buto (Fig. 11) where there appears to have been a two stage deposition process: first fluvial, then by wind (Wunderlich, 1989). Similar observations were made by Tronchère et al. (2012, 2009) based on microscopic analysis and architectural considerations of a deposit they termed the “pre-Pelusiatic transition layer”. The unit’s presence has also been inferred in other surveys (El-Awady, 2009; El-Shahat et al., 2005; Judd, 1897) where well-sorted, friable, very fine to medium sands at the top of the Mit Ghamr Formation were also attributed to their having been redeposited by wind.

5.3. The Transgressive Sand Formation

The “early Holocene transgressive sand” is a sedimentary unit that was defined during the MEDIBA survey (Stanley et al., 1996). The unit is composed of coarse, poorly-sorted, olive-grey to yellowish-brown quartzose sands which contain a high percentage of heavy minerals, as well as mollusc and echinoderm fragments, mica and lithic clasts, plus pelecypods, gastropods, ostracods and foraminifera (Arbouille and Stanley, 1991; Chen et al., 1992; Coutellier and Stanley, 1987; El-Shahat et al., 1999; Stanley et al., 1992). The sands are not stained by iron oxide, in contrast to the Mit Ghamr Formation (El-Shahat et al., 1999). These deposits were probably originally fluvial sediments that incorporated a littoral signature during retrogradation of the shoreline and major reworking by waves and other coastal processes between c.15,000–8000 cal BP (Stanley et al., 1992).

5.4. The Bilqas Formation

First recognised as a distinctive unit under the name of “terre végétale” (Fourtau, 1915), the Bilqas Formation (Rizzini et al., 1978) makes up the “alluvial mud” of the delta plain. It is divided into four, with the most important conceptual contribution of the current synthesis being the division of the fluvially-dominated delta sediments into two units: Bilqas 2 and Bilqas 1.

5.4.1. “Modern Aeolian” Member:

This unit of convenience is represented by sediments which have been deposited by aeolian activity on top of the floodplain; it is also applied to significant quantities of archaeological debris at “tell” sites when encountered in cores from the surface downwards. These deposits of anthropogenic origin originally stood above the floodplain, acting as a trap for such windblown material, and also underwent degradation and aeolian reworking *in situ*. The unit usually occurs both at the margins of the delta, and on “tell” sites within the delta.

5.4.2. Coastal Member:

This sedimentary unit represents all sediments interpreted as having being deposited in a coastal, nearshore or marine setting, except for the Transgressive Sand Formation, which is excluded from this grouping as it occupies

a very specific stratigraphic position at the base of the Holocene sequence. The Coastal Member, on the other hand, is contemporaneous with much of the deposition of the fluvial units of Bilqas 1 and Bilqas 2. This unit contains marine, semiterrestrial, coastal, estuarine, lagoonal and occasionally sabkha deposits; the spatio-temporal extents of these sedimentary environments have been previously mapped (Arbouille and Stanley, 1991; Chen et al., 1992; Coutellier and Stanley, 1987; Stanley et al., 1992).

5.4.3. *Bilqas 1 and Bilqas 2 Members:*

The recent fluvial sequence is divided into Bilqas 1 and Bilqas 2 Members. In this twofold division, the Bilqas 2 Member is the lower of the two units. It is made up of bluish-black silty-clay to clayey-silt containing a high percentage of organic matter. Peat layers are locally developed, and spatial variations in grain size are rapid and unpredictable, in that units do not tend to grade into each other over wide areas. It is thought to represent deposition within the LSC environment discussed in section 2. This is in contrast to the overlying Bilqas 1 Member which is generally brown-grey in colour, less rich in organic material, and very predictable in the lateral variation of its grain size. This later unit represents overtopping of levees and the development of a wide floodplain during the later Holocene, within the “Meandering” environment (section 2).

The contact between the Bilqas 2 and Bilqas 1 units therefore corresponds to the LSC–Meandering Transition, an event suggested by Pennington et al. (2016) to be driven by the slowing of bulk aggradation rates, driven ultimately by the slowing of sea-level rise within the context of a weakening monsoonal system. This position is revisited and discussed further below in section 7.

The lower, Bilqas 2 unit is first thought to have been observed in the eastern delta by the Amsterdam University Survey Expedition to the Nile Delta (AUSE project), where it was labelled as “Nile 2 deposits”. It was described as comprising rapidly-alternating deposits of silt and sand; dark, organic, humic clays; and calcareous clays (de Wit and van Stralen, 1988b) suggesting “permanent water-bearing systems...such as larger rivers, swamps and lakes...[with] no obvious traces of temporal desiccation”, in combination with “ephemeral stream sediments...[and] wadi-fed stagnant pools”. These lower units give way to overlying “Nile 1” facies (Fig. 11), which comprise very different sediments (Bilqas 1 Member): “uniform flood-basin clays, levee silts, channel plugs, and intermittent eolian sandy influxes” (de Wit, 1993).

The rapidly-alternating nature of the deposits of the Bilqas 2 Member in a lateral sense suggests deposition in an environment characterised by anastomosing streams with narrow levees surrounding larger floodbasins: an exact picture of the LSC environment. The humic muds would have been deposited within the swamps between these channels. The rapidly-alternating nature of the lower deposits in a vertical sense is the result of the likely very

dynamic and changeable landscapes in which they were laid down: again a hallmark of the LSC environment, and in direct contrast to the sediments above.

A very similar sequence was also observed around Minshat Abu Omar (Fig. 11), where a lower unit of “compact dark grey violet mud, rich in organic material” (Krzyżaniak, 1993) gives way to sediments which contain less organic matter, and within which “soil development is documented by calcic nodules, oxic mottles and iron-manganese concretions” (Andres and Wunderlich, 1992, 1991). The lower unit was interpreted as “indicat[ing] the prevalence of semiterrestrial environments” (Andres and Wunderlich, 1991), and is correlated here as the Bilqas 2 Member. The upper sediments originate from a much more well-drained setting, and are correlated as the Bilqas 1 Member. The whole sequence is underlain by greenish-grey sand deposits, which are coloured as such as a result of reduced iron (Andres and Wunderlich, 1991) – presumably in-situ decomposition of vegetation within the swamps of Bilqas 2 unit above resulted in reducing environments persisting below the surface.

In the western delta, the same sedimentary sequence has also been observed by the Buto Regional Survey (BRS) (Wunderlich, 1989; Wunderlich and Andres, 1991), the Mansoura Western Delta Survey (MUWDS) (El-Awady, 2009), around Sais (El-Shahat et al., 2005), and in recent fieldwork at Kom Geif, Kom al-Ahmer/Kom Wasit and Tell Mutubis (Fig. 11). All these coring surveys also divided the Bilqas Formation into two units: a lower unit containing humic muds rich in organic matter (Bilqas 2 Member), sometimes containing peat layers and smelling of hydrogen sulphide, and an upper one (Bilqas 1 Member) which has no peat layers, is browner in colour, contains rhizoconcretions and displays more predictable variations in grain-size. Once again, the substantial lateral inhomogeneity in grain size in the lower unit is taken as an indication of small anastomosing streams separating isolated floodbasins, while the smell of hydrogen sulphide and existence of peat is taken as indicating an organic rich, wetland landscape with standing water and euxinia persisting in the subsurface.

Palynological evidence also supports a division of the sedimentary sequence in two, with the lower unit reflecting more marshy environments than the upper. An undated pollen record from the coastal margin (Saad and Sami, 1967) shows an upwards decrease in semi-aquatic species such as Cyperaceae, Poaceae, Typhaceae and *Jussieuia*, and an increase in land plants. Tentative correlation of this core with nearby dated boreholes of the MEDIBA survey suggest this transition could have taken place after 8000–5300 cal BP. A further study (Leroy, 1992) also in general found progressively decreasing amounts of Cyperaceae and other wetland plants, and increasing Poaceae, Amaranthaceae and Chenopodiaceae since c.4000 cal BP. More recent work (Bernhardt et al., 2012; Hennekam et al., 2015) has also found decreasing Cyperaceae c.5000 cal BP, which may reflect the replacement of local wetland land-

scapes of the Bilqas 2 environment by the Bilqas 1 facies.

6. Delta Evolution

Fig. 12 shows the overall modelled landscape evolution of the Nile Delta c.8500–4500 cal BP, characterised overwhelmingly by the genesis and subsequent disappearance of LSC landscapes, represented by deposits of the Bilqas 2 Member, and their replacement by more well-drained floodplains of the Bilqas 1 Member. These landscapes were laid down upon a “pre-delta” topographic surface formed by the Mit Ghamr and Geziracover Formations (Fig. 7). Prior to c.8000 cal BP, the area now covered by the modern delta plain was made up of deposits of the Mit Ghamr Formation and Geziracover Formation. Rivers were incising, redepositing and reworking earlier fluvial material, with aeolian deposition of the Geziracover Formation on some topographic highs.

The onset of Bilqas deposition and the inception of the Holocene alluvial delta plain first occurred around 8000 cal BP in the northern part of the delta (Fig. 12a). Data from the MEDIBA survey (Stanley et al., 1996; cores S38 and S32) as well as from Minshat Abu Omar (Andres and Wunderlich, 1991; core D5) show that around 8000 cal BP deposits of the Bilqas 2 unit were being laid down in the extreme north of the delta. Further south, rivers were still behaving as before, and the Mit Ghamr and Geziracover units were still fully exposed at the surface, as shown by an OSL date from Tell ed-Dab^a (Tronchère et al., 2012) which comes from within the Geziracover Formation.

The onset of Bilqas 2 deposition in the central, eastern and western delta probably came about at c.8000–7500 cal BP, a date-range constrained by the lowermost date within core S87 of the MEDIBA survey (Stanley et al., 1996), which shows the initiation of Bilqas deposition in the central delta at c.8155–7615 cal BP. Nearby core S86 (Stanley et al., 1996) also corroborates this time-frame, with lowermost dated Bilqas deposits at 7571–7156 cal BP. The lowest AUSE project radiocarbon date (within the Bilqas 2 unit) also points to the onset of Bilqas deposition at some point earlier than c.7250–6750 cal BP (de Wit, 1993); at Sais deposition of the Bilqas 2 unit is also initiated before c. 7450–5850 cal BP (Wilson, 2006b; Wilson et al., 2014).

The topography of the delta at this time was moderately undulating, with hills standing over 5m taller than the floodplain in many locations, especially at the delta fringes (Fig. 12a). The shoreline was situated substantially inland relative to its present position, particularly in the east (Coutellier and Stanley, 1987). Very little is known about the exact character of the coastal margin at this time, although it is probable that barrier-beaches were just beginning to form. The near-offshore was dominated by littoral-zone deposits of the Transgressive Sand Formation (Stanley and Warne, 1993a).

After the onset of Bilqas deposition at c.7500 cal BP and until c.6000 cal BP it seems that much of the fluvial part of the delta was experiencing deposition of the Bilqas

2 unit, hosting landscapes characterised by dynamic, anastomosing channel networks and swampy floodbasin facies of the LSC environment (Fig. 12b). Between 7500–6000 cal BP there was extensive peat development of the Bilqas 2 unit at Buto (Wunderlich, 1989), and deposits of the Bilqas 2 unit are also interpreted to have been encountered within some of the MEDIBA cores along the coastal margin (Stanley et al., 1996), as well as at Minshat Abu Omar (Andres and Wunderlich, 1991). The southernmost extent of the unit is not known, but it was certainly further south than the AUSE study area, with some cores in the central delta area also suggesting its presence. To the far south deposits of the Mit Ghamr and Geziracover Formations probably still cropped out at the surface. Sandy hills still protruded above the floodplain especially near the delta fringes. The shoreline prograded extensively in the western delta, behind which lagoons were developed (Warne and Stanley, 1993b), while marshy wetlands behind small barrier beaches persisted in the east (Coutellier and Stanley, 1987).

From 6000–5500 cal BP, overall aggradation rates fell (Fig. 8), and the fluvial landscape changed dramatically. While Bilqas 2 sediments, corresponding to dynamic, swampy and marshy environments were still being deposited in the north, deposition of the Bilqas 1 Member appears to have commenced in the southern and central part of the delta (Fig. 12c), characterised by much more extensive, well-drained floodplains, single-channel networks and less marshy landscapes. The second date from the AUSE project, at some c.6000 cal BP, is from within the Bilqas 1 unit (de Wit, 1993); similarly a date within core S86 of the MEDIBA survey at 5906–5334 cal BP (Stanley et al., 1996) could also be from within the Bilqas 1 unit. This suggests that Bilqas 1 deposition had been initiated by c.6000–5500 cal BP in the central part of the delta.

However, in the north of the delta Bilqas 2 sediments were still being deposited: various cores at Minshat Abu Omar (Andres and Wunderlich, 1991, 1992) still record Bilqas 2 sedimentation, as does core S9 of the MEDIBA survey and a number of cores at Buto. The same overall areas of turtlebacks remained, although they were reduced in size compared to previous time periods. In the coastal area, lagoons persisted in the western and central regions (Warne and Stanley, 1993a), while across the delta fringe a coastal barrier-beach system had clearly been established (Arbouille and Stanley, 1991; Stanley et al., 1992).

Butzer (2002) suggests there is a delta-wide unconformity around 6000 cal BP, based on the fact that at some “tell” sites fans of reworked sandy material appear to extend into the floodplain at this time. However, this is not seen in all studies (see Fig. 11), and the exact lithostratigraphic relationships of the fans to the sediments above and below is not always clear.

By 4500 cal BP the area of Bilqas 1 deposition had expanded significantly northwards to cover most of the delta (Fig. 12d); Bilqas 2 sedimentation was extremely localised in the far north. However, Bilqas 2 deposition did continue

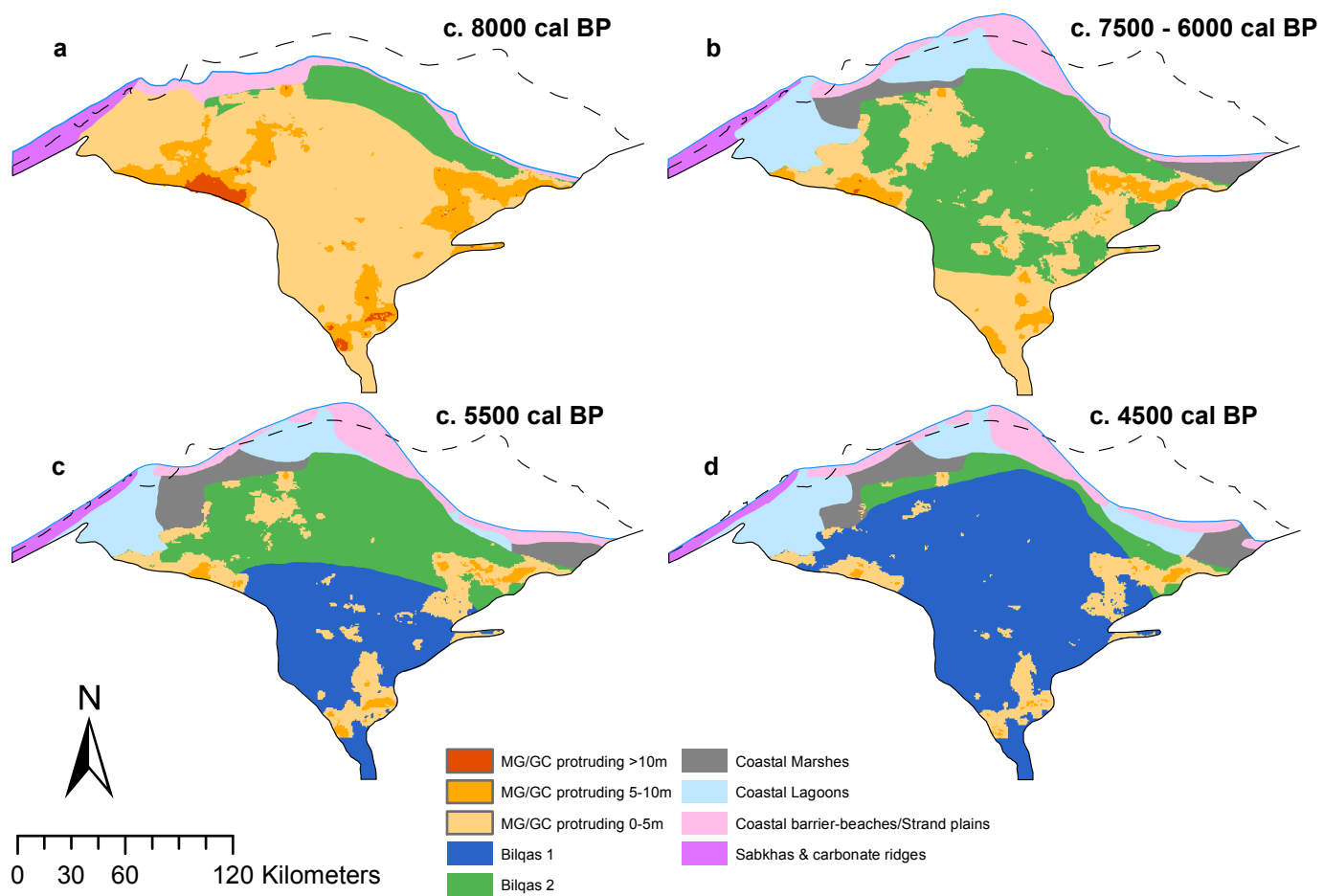


Figure 12: Best estimate maps showing the mid-Holocene evolution of the Nile Delta c.8000–4500 cal BP: a) c.8000 cal BP b) c.7500–6000 cal BP c) c.5500 cal BP d) c.4500 cal BP. The dashed line on each subfigure indicates the modern-day coastline; MG/GC= Mit Ghamr/Geziracover Formation.

in a number of limited areas in the extreme north-east and north-west delta: cores D71 and D4 at Minshat Abu Omar and MEDIBA cores S55 and S54 to the north of Buto suggest continuing Bilqas 2 deposition in these locations persisting until at least c.4500 cal BP, and possibly much later. The previously substantial turtlebacks were by this time much more limited in extent; the eastern delta was now actively prograding (Coutellier and Stanley, 1987) but extensive lagoons, marshes and barrier beaches remained the main features of the coastal zone (Stanley and Warne, 1993a).

Since 4500 cal BP, the overall landscapes of the Bilqas 1 Member have generally continued to exist until the present day, albeit with significant anthropogenic alteration. They have been modified and exploited as a result of the development of irrigation agriculture, the digging and maintenance of natural and artificial waterways (Butzer, 1976; Cooper, 2014; Hassan, 2010), and most recently through the draining of the coastal lagoons, and the building of the Aswan High Dam which has starved the delta of 95% of its sediments (Stanley and Warne, 1998).

In summary, the data support the initiation of Bilqas 2 deposition at c.8000–7500 cal BP near the shoreline. The spatial extent of the unit and its corresponding environments of swampy floodbasins then expanded upstream until c.6000 cal BP, after which it was replaced by Bilqas 1 sediments and a less swampy landscape from the south. These environments pushed northwards between 6000 and 5000 cal BP. By c.4500 cal BP Bilqas 2 sediments were being deposited in only a limited number of areas; by c.3500 cal BP they had disappeared completely, and the environments of the Bilqas 1 Member dominated to the present day. Turtlebacks – a common landscape feature in the delta prior to some 6000 cal BP – gradually diminished in size and became much more limited in their spatial extent by 4500 cal BP. Importantly these also seem to have been smaller than earlier syntheses suggested (Butzer, 2002, 1976, 1974). The coastline prograded in the west from c.8000 cal BP, and has broadly approximated its modern-day position since 6000BC. In the east, however, an extensive coastal embayment persisted, and the shoreline prograded only from c.5000 cal BP, reaching its modern position just in the last two thousand years (Coutellier and Stanley, 1987; Goodfriend and Stanley, 1999; Moshier and El-Kalani, 2008).

These landscape changes taking place in the delta were larger than those occurring upstream during this time period. While upstream there was also an early mid-Holocene replacement of sandy sediments by silts (Adamson et al., 1980; Butzer, 1998; Toonen et al., in press) – analogous to the onset of deposition of the Bilqas Formation – the later mid-Holocene period upstream saw no episodes of complete landscape remodelling analogous to the Bilqas 2 – Bilqas 1 transition. The major upstream landscape changes were instead related to periods of floodplain and channel network contraction, possibly associated with decreased discharge, regional aridification and cooling (Mack-

lin et al., 2015).

6.1. Aggradation history

Aggradation rates display a decreasing trend through time that correlates with decreasing rates of sea-level rise (Fig. 8). Prior to 5200–5950 cal BP, aggradation rates appear to range approximately between 2.4–12mm/yr; after this time they are lower, generally between c. 0.5–1.5mm/yr (Fig. 9). This decrease in aggradation rates appears to lag the inflexion in the rate of sea-level rise by some 750 years. This lag may be real, or it may be an artefact, since the sea-level curve is not from Egypt but from Israel (no reliable sea-level curves have been constructed for this period for Egypt). In general, however, the fact that aggradation rates decrease through time following the sea-level curve is a strong indication that they are controlled predominantly by downstream factors.

Aggradation rates are not homogenous across the delta, however (Fig. 9). To establish whether these differences are caused by regional east-west faulting patterns (Bosworth, 2008; Hussein et al., 2013; Tingay et al., 2011), the age-depth data was plotted against latitude and longitude (Fig. 13). This figure clearly shows there is no detectable latitudinal trend within the data – points of equal size (equal age) lie along the horizontal – and therefore suggests that east-west regional faulting is not contributing to regional variability in subsidence patterns. It further provides proof that any east-west trending tectonic “hinge-line” of high rates of subsidence (Stanley and Warne, 1993a) lies further to the north than the data considered.

However, there appears to be a longitudinal variation in aggradation rate. Deposits of similar age are buried approximately 1-2m deeper in the West and North-West regions of the fluvial zone than in the East and North-East (Fig. 13); the west has experienced faster aggradation than the east. Such a trend is also suggested by modern-day topography, and the depth to “pre-delta” deposits (Fig. 7): turtlebacks are exposed in the east, but not in the west, where they have presumably been buried. Importantly this subsidence is in the opposite direction to that north of the hinge-line, where deposits are more deeply buried in the east (Stanley, 1990).

This deeper burial of deposits in the west could be caused by a variety of factors. It is highly unlikely to be caused by autocompaction within the Holocene deposits, since it is not just the Holocene sediments that are buried at different depths: the subsidence of the underlying “pre-delta” topography and turtlebacks suggests that the subsidence must have affected the full Quaternary stratigraphy of the delta. It is also probably not due to the influence of the “Pelusium Line” (Said, 1981, p. 56) – a controversial hypothesised transcontinental fault shear system (Neev, 1977, 1975), since even studies that support the existence of this fault system do not place it in a location that could account for the distribution of turtlebacks (Gamal, 2013). Neither is it likely to be as a result of greater original accommodation space in the west, since some of the oldest

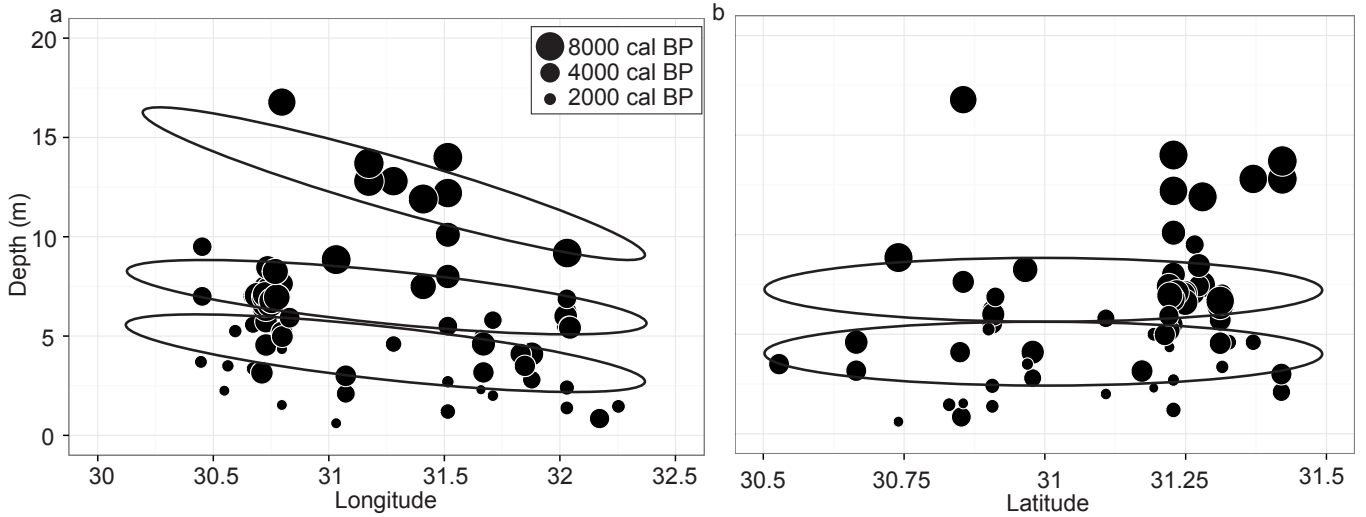


Figure 13: Age and depth of deposits plotted with respect to cardinal directions: a) Depth vs Longitude. b) Depth vs Latitude. The size of the bubbles represents age (larger=older).

dated deposits of the Bilqas Formation have been found in the east by the AUSE project; if the western delta were at a lower elevation than the east during the early mid-Holocene then onlap of the Bilqas Formation in the east would have been a later phenomenon. It is therefore more likely a result of a deep control such as differential autocompaction within the full Quaternary or Cenozoic sequence, or longer wavelength patterns of lithospheric flexure.

7. Discussion – drivers of landscape evolution

The mid-Holocene landscape evolution of the Nile Delta has been ultimately governed by a decrease in the rate of relative sea-level rise, although subsidence, changes in sediment-supply dynamics driven by a changing monsoonal system and humans have also played major roles.

7.1. Sea-level rise

Relative sea-level change (comprising glacio-isostatic, hydro-isostatic and eustatic components) has played the defining role in the landscape evolution of both the coastal and fluvial regions of the Nile Delta throughout the Holocene.

In the fluvial region of the delta, increased base-level initially resulted in a decrease in river gradient and the deposition of the Bilqas Formation (Stanley and Warne, 1994). High rates of sea-level rise then resulted in the development of the LSC landscape as represented by the Bilqas 2 Member in the early mid-Holocene. The decrease in the rate of sea-level rise in the later mid-Holocene then ultimately resulted in the LSC-Meandering Transition and the development of the more homogenous floodplains of the Bilqas 1 Member, as described at length in section 2.

Further north, in the coastal zone, the changing landscapes have also been governed by the rate of relative sea-level rise: high rates prior to 7500 cal BP resulted in the

marine transgression extending to areas far inland of the present shoreline and the deposition of the Transgressive Sand Formation (Flaux et al., 2013; Stanley and Warne, 1993a). Following the slowing-down of the rate of sea-level rise, sediments were reworked into extensive beach-barrier systems which served to close-up the coastline and halt marine ingressions (Stanley and Warne, 1993a). As sea-level rise slowed further the shoreline gradually prograded northwards to its current position.

7.2. Subsidence

In addition to this regional sea-level signal, local tectonic effects and subsidence have been important in controlling the spatially heterogeneous evolution of the delta, contributing in the coastal zone specifically to a more extensive transgression (and subsequent progradation) in the east compared to the west. While an east-west trending “hinge-line” has caused high rates of subsidence of Holocene deposits along the coastal margin relative to the area more landward (Stanley and Warne, 1993a), the spatial pattern of subsidence north of this hinge-line is heterogeneous, and is such that lagoonal areas have experienced higher rates of subsidence than the zones in between, with many of the highest rates around the Manzala region in the east (Stanley and Clemente, 2014). These differential patterns in subsidence could be caused by differences in tectonic activity resulting from reactivation of faulted basin structures (Stanley, 1990, 1988; Stanley and Warne, 1997), or lithospheric flexure caused by differences in Holocene sediment loading, in turn driven by increased autocompaction of lagoonal deposits compared to coarser clastic deposits (Marriner et al., 2012b). Whatever the cause, these patterns of subsidence resulted in a further landward transgression that persisted for longer in the eastern delta compared to the west.

In the fluvial zone regionally variable subsidence has also occurred: deposits in the west have subsided more than those in the east. This variability does not seem to have been caused by either faulting, subsidence within the Holocene section or the amount of original accommodation space, but may be related to differential autocompaction of Pleistocene or earlier deposits, or longer-wavelength patterns of lithospheric flexure. This heterogeneous pattern of subsidence needs to be considered (for example) when studying the spatial distribution of archaeological sites.

7.3. *Hydroclimatic changes and sediment-supply*

The early and mid-Holocene time periods are also characterised by substantial climatic change and hydroclimatic variability in the Nile Basin. From c. 11000 to 6000 cal BP the region experienced significantly higher precipitation than at present, and the Sahara hosted a savanna ecosystem with permanent lakes (de Menocal et al., 2000; Fleitmann et al., 2003; Gasse, 2000; Kröpelin et al., 2008). The onset of this “African Humid Period” (AHP) was driven by increasing northern hemisphere insolation and concomitant northward movement of the ITCZ in the late Pleistocene; its end was similarly forced by the reverse mechanism during the mid-Holocene (Williams, 2009). Most studies point towards a gradual transition to a more arid climate between c. 9000 and 5000 cal BP (Shanahan et al., 2015).

Hydrological changes associated with these climatic shifts are certainly responsible for aspects of the delta’s landscape evolution. As well as being forced by a decrease in river gradient (section 7.1), the onset of deposition of the Bilqas Formation is also probably related to the onset of the AHP. Increased vegetation and reduced erosion in the Nile catchment likely resulted in the river changing from being dominated by sandy bedload to a silty suspended load, which was deposited across the Nile floodplain (Adamson et al., 1980; Said, 1993).

The subsequent termination of the AHP then contributed to the mid-Holocene landscape changes explored within this paper. The Bilqas 2 to Bilqas 1 transition could have in part also been driven by hydroclimatic shifts. Decreasing rates of sediment-supply probably also played a role in forcing the Bilqas 2 – Bilqas 1 transition, through the same mechanism of stimulating lower in-channel aggradation rates. These decreasing sedimentation rates between 7700 and 1200 cal BP are clear from a variety of onshore and offshore records, and have been linked to a decrease in monsoon intensity over the Ethiopian highlands (Blanchet et al., 2014; Marriner et al., 2012a; Marriner et al., 2013; Revel et al., 2015 – although see Krom et al. (2002) for a different view). Decreased discharge could also have played a role in the transition from an anastomosing to a single-channel regime, by analogy with similar changes further upstream (Macklin et al., 2015, 2013; Woodward et al., 2001).

In the coastal zone specifically, a change from a freshwater to a marine system in the Mareotis lagoon around

6750 cal BP (Flaux et al., 2011) has been explained as a consequence of the ending of the AHP, resulting from either a shift in the hydrological budget of the area as a result of reduced Nile discharge (Flaux et al., 2013), or marine influx as a result of the erosion of protective beach-barrier systems due to a concomitant reduction in sediment-supply (Marriner et al., 2013).

Overall, it is clear that a variety of hydroclimatic factors contributed to bulk geomorphological change across the delta during the mid-Holocene. These forcing factors are not always easy to disentangle from the primary driver of decreased rates of sea-level rise.

7.4. *Human impact*

Human influences have played a role in the landscape development of the delta plain, but in general probably not to a major extent within the time periods considered within this synthesis. It is only since c.3000–2000 cal BP that variability in the effectiveness of irrigation and canalisation strategies have been shown to have demonstrably had a major impact on the biosedimentary and hydrological budget of the Mareotis lagoon, masking more “natural” changes (Flaux et al., 2012). Pollen records have also shown a much greater human impact on the local environment over the last 3000 years (Stanley and Bernhardt, 2010). The history of human influences on the delta landscapes over these later periods have been reviewed elsewhere (Cooper, 2014). Most recently, of course, the delta has become intensively farmed, and the reduction in sediment supply caused by the building of the Aswan High Dam has resulted in fast rates of erosion (Stanley and Warne, 1998), a situation exacerbated further by increased rates of sea-level rise resulting from anthropogenic climate change.

8. **Conclusions**

This paper suggests that the mid-Holocene environmental evolution of the Nile Delta was characterised by the replacement of “Large-Scale Crevassing” environments (dynamic, swampy wetlands with extensive floodbasins and anastomosing channels), by more well drained, less dynamic floodplains hosting single-channel river networks with wide levees. The sediments which record these two different environments are named here as the the Bilqas 2 and Bilqas 1 Members, and sit within an updated stratigraphic framework for the uppermost Nile Delta deposits.

The “Large-Scale Crevassing” environments first existed near the shoreline c.8000 cal BP, before they expanded to cover much of the delta plain for the next two or three millennia. Then, between c.6000–5000 cal BP they were replaced by the later, better-drained floodplain environments. Throughout this time period, topographic highs within the fluvial plain (turtlebacks) also became smaller and less pronounced in their relief, while the contemporaneous development of the coastal zone was marked by

the “closing-up” of the shoreline by barrier beaches, subsequent progradation, the development of coastal lagoons and marshes, and the establishment of a clear separation between the marine and fluvial domains.

These changes in the landscape were some of the most major environmental shifts taking place in the Nile basin during this time, and were effected primarily by a mid-Holocene decrease in the rate of relative sea-level rise, within the context of weakening Nile discharge due to hydroclimatic changes associated with the ending of the “African Humid Period”.

While the landscape models presented in this paper represent the best available synthesis of the Nile Delta’s mid-Holocene evolution, they still provide only a general picture of bulk landscape change, at a relatively coarse level of resolution. To move beyond this there is a real need to collect more chronostratigraphic and other data, particularly from the central and southern delta.

However, even as the models stand they are sufficient to begin to be used for site prediction purposes. Archaeological exploration for early sites should focus on the areas of reconstructed turtlebacks, where many Predynastic settlements were founded (Maczyńska, 2011, p. 886). A particular area of note is that around Buto in the north-west delta. Comprising an area of sandy hills but with easy access to large, productive coastal lagoons and wetlands as well as the fluvial floodplain, and having a connection to the sea, this would have been a prime position for early settlement.

The models can also begin to be incorporated into discussions of contemporaneous developments in the human sphere over the *longue durée*. Relationships exist between rivers, their environments and channel networks, and societal change (Giosan et al., 2012; Hassan, 1997; Jotheri et al., 2016; Macklin and Lewin, 2015), and social trajectories leading to the emergence of the ancient Egyptian state c.5050 cal BP need to be considered in light of the environmental evolution presented in this paper.

In particular, the delta-wide transformation revealed here between 6000 and 5000 cal BP would have had a significant archaeological impact in relation to agricultural technologies. This time period is one in which the economic basis of (Lower) Egyptian society broadly changed from a mixed strategy involving fishing, hunting, herding and low level agriculture, to a predominantly agrarian mode of subsistence reliant upon floodwater farming of cereals (Hassan, 2010; Tassie, 2014). Such a shift could be interpreted in terms of these changing environments (Pennington et al., in prep.). The dynamic wetland landscapes of the Bilqas 2 Member may not have been so conducive to intensive cereal agriculture, instead affording opportunities centering on the exploitation of aquatic resources (Wilson et al., 2014). The subsequent change to drier floodplains behind levees would have facilitated agricultural expansion and intensification and the move from subsistence activities to the production of a surplus. This could then have funded population growth, leading to the foundations

of later social complexity (Castillos, 2011; Hassan, 2010; Kemp, 2006).

Further targeted geoarchaeological and archaeological research at both a local and regional scale within the delta will be able to inform more on specific links between the natural landscape and human culture.

Supplementary Data

The chronostratigraphic and lithostratigraphic databases for the fluvial zone of the delta used in the production of the models are provided as supplementary data to this publication.

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References

- Abu El-Ella, R., 1990. The Neogene-Quaternary section in the Nile Delta, Egypt: geology and hydrocarbon potential. *Journal of Petroleum Geology* 13 (3), 329–340.
- Adamson, D. A., Gasse, F., Street, F. A., Williams, M. A. J., 1980. Late Quaternary history of the Nile. *Nature* 288 (5786), 50–55.
- Andres, W., Wunderlich, J., 1986. Untersuchungen zur Paläogeographie des westlichen Nildeltas im Holozän. *Märburger Geographische Schriften* 100, 117–131.
- Andres, W., Wunderlich, J., 1991. Late Pleistocene and Holocene evolution of the eastern Nile Delta and comparisons with the western Delta. In: Brückner, H., Radtke, U. (Eds.), *Von der Nordsee bis zum Indischen Ozean*. Steiner, Stuttgart, pp. 121–130.
- Andres, W., Wunderlich, J., 1992. Environmental conditions for early settlement at Minshat Abu Omar, eastern Nile Delta, Egypt. In: van den Brink, E. C. M. (Ed.), *The Nile Delta in Transition: 4th–3rd millennium BC*. IES, Tel Aviv, pp. 157–166.
- Arbouille, D., Stanley, D. J., 1991. Late Quaternary evolution of the Burullus lagoon region, north-central Nile Delta, Egypt. *Marine Geology* 99 (1–2), 45–66.
- Aslan, A., Autin, W. J., Blum, M. D., 2005. Causes of river avulsion: insights from the late Holocene avulsion history of the Mississippi River, U.S.A. *Journal of Sedimentary Research* 75 (4), 650–664.
- Attia, M. I., 1954. *Deposits in the Nile Valley and the Delta*. Government Press, Cairo.
- Bernhardt, C. E., Horton, B. P., Stanley, D. J., 2012. Nile Delta vegetation response to Holocene climate variability. *Geology* 10 (7), 615–618.
- Bietak, M., 1975. Tell el-Dab’a II: Der Fundort im Rahmen einer archäologisch-geographischen Untersuchung über das ägyptische Ostdelta. Verlag der Österreichischen Akademie der Wissenschaften, Vienna.
- Blanchet, C. L., Frank, M., Schouten, S., 2014. Asynchronous changes in vegetation, runoff and erosion in the Nile river watershed during the Holocene. *PLOS One* 9 (12), 1–18.
- Bosworth, W., 2008. North Africa - Mediterranean present-day stress field transition and implications for fractured reservoir production in the eastern Libyan basins. In: Salem, M., Oun, K., Essed, A. (Eds.), *Geology of East Libya Vol. 4: Proceedings of the Third Symposium of the Sedimentary Basins of Libya*. Earth Sciences Society of Libya, Tripoli, pp. 123–138.
- Brown, A. G., 1997. *Alluvial Geoarchaeology: Floodplain archaeol-*

- ogy and environmental change. Cambridge University Press, Cambridge.
- Buck, P. E., 1990. Structure and Content of Old Kingdom Archaeological Deposits in the Western Nile Delta, Egypt: A geoarchaeological example from Kom El Hisn. Ph.D. thesis, University of Washington.
- Buck, P. E., 2016. Geomorphology and regional fluvial reconstruction and history. In: Wenke, R. J., Redding, R. W., Cagle, A. J. (Eds.), *Kom el-Hisn (ca. 2500 – 1900 BC): An ancient settlement in the Nile Delta of Egypt*. Lockwood Press, Atlanta, pp. 53–70.
- Bunbury, J. M., 2013. Geomorphological development of the Memphite floodplain over the past 6000 years. *Studia Quaternaria* 30 (20), 61–67.
- Butzer, K. W., 1959. Environmental and human ecology in Egypt during Predynastic and Early Dynastic times. *Bulletin de la Société de Géographie d'Égypte* 32, 43–87.
- Butzer, K. W., 1974. Delta. In: Helck, W. (Ed.), *Lexikon der Ägyptologie* 1. Harrassowi, Wiesbaden, pp. 1043–1052.
- Butzer, K. W., 1976. *Early Hydraulic Civilization in Egypt*. University of Chicago Press, Chicago.
- Butzer, K. W., 1998. Late Quaternary problems of the Egyptian Nile: stratigraphy, environments, prehistory. *Paléorient* 23 (2), 151–173.
- Butzer, K. W., 2002. Geoarchaeological implications of recent research in the Nile Delta. In: van den Brink, E. C. M., Levy, T. E. (Eds.), *Egypt and the Levant: Interrelations from the 4th through the early 3rd millennium BCE*. Leicester University Press, London, pp. 83–97.
- Castillos, J. J., 2011. The development and nature of inequality in early Egypt. In: Friedman, R., Fiske, P. N. (Eds.), *Egypt at its Origins 3: Proceedings of the third international conference "Origin of the State. Predynastic and Early Dynastic Egypt"*, London, 27th July – 1st August 2008. Peeters, Leuven, pp. 1243–1253.
- Chen, Z., Stanley, D. J., 1993. Alluvial stiff muds (Later Pleistocene) underlying the lower Nile Delta plain, Egypt: petrology, stratigraphy and origin. *Journal of Coastal Research* 9 (2), 539–579.
- Chen, Z., Warne, A. G., Stanley, D. J., 1992. Late Quaternary evolution of the northwest Nile Delta between Rosetta and Alexandria, Egypt. *Journal of Coastal Research* 8 (3), 527–561.
- Clarke, J., Brooks, N., Banning, E. B., Bar-Matthews, M., Campbell, S., Clare, L., Cremaschi, M., di Lernia, S., Drake, N., Gallinaro, M., Manning, S., Nicoll, K., Philipm, G., Rosen, S., Schoop, U.-D., Tafuri, M. A., Weninger, B., Zerbonig, A., 2016. Climatic changes and social transformations in the Near East and North Africa during the long 4th millennium BC: a comparative study of environmental and archaeological evidence. *Quaternary Science Reviews* 136, 96–121.
- Cockerton, H. E., Street-Perrott, F. A., Barker, P. A., Leng, M. J., Sloane, H. J., Ficken, K. J., 2015. Orbital forcing of glacial/interglacial variations in chemical weathering and silicon cycling within the upper White Nile basin, East Africa: stable-isotope and biomarker evidence from Lakes Victoria and Edward. *Quaternary Science Reviews* 130, 57–71.
- Cooper, J. P., 2014. *The Medieval Nile: Route, navigation, and landscape in Islamic Egypt*. The American University in Cairo Press, Cairo.
- Coulson, W., 1996. *Ancient Naukratis II.1: The survey at Naukratis*. Oxbow Books, Oxford.
- Coutellier, V., Stanley, D. J., 1987. Late Quaternary stratigraphy and paleogeography of the eastern Nile Delta, Egypt. *Marine Geology* 77 (3-4), 257–275.
- Dawod, G., Ismail, S., 2005. Enhancing the integrity of the national geodetic base in Egypt: Proceedings of the FIG working week and GSDI-8 international conference. International Federation of Surveyors, Cairo.
- Dawod, G. M., Mohamed, H. F., Ismail, S. S., 2010. Evolution and adaption of the EGM2008 geopotential model along the northern Nile Valley, Egypt: case study. *Journal of Surveying Engineering* 136, 36–40.
- de Menocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., Yarusinsky, M., 2000. Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing. *Quaternary Science Reviews* 19 (1-5), 347–361.
- de Wit, H. E., 1993. The evolution of the Eastern Nile Delta as a factor in the development of human culture. In: Krzyzaniak, L., Kobusiewicz, M., Alexander, J. (Eds.), *Environmental Change and Human Culture in the Nile Basin and Northern Africa until the 2nd millennium B.C*. Poznań Archaeological Museum, Poznań, pp. 305–320.
- de Wit, H. E., van Stralen, L., 1988a. Geo-archaeology and ancient distributaries in the eastern Nile delta: results of the 1987 AUSE survey in Sharqiya, Egypt. Tech. Rep. 34, Laboratory of Physical Geography and Soil Science, University of Amsterdam, Amsterdam.
- de Wit, H. E., van Stralen, L., 1988b. Preliminary Results of the 1987 palaeo-geographical survey. In: van den Brink, E. C. M. (Ed.), *The Archaeology of the Nile Delta: Problems and priorities*. Netherlands Foundation for Archaeological Research in Egypt, Amsterdam, pp. 135–139.
- Dorner, J., 1994. Die Rekonstruktion einer pharaonischen Flusslandschaft. *Mitteilungen der Anthropologischen Gesellschaft in Wien* 123/124, 400–405.
- Dorner, J., 1999. Die Topographie von Piramesse - Vorbericht. *Ägypten und Levante* 9, 77–83.
- El-Awady, H. M. S., 2009. Application of the geophysical survey for environmental and archaeological purposes, central western part of the Nile Delta, Egypt. Unpublished MSc Thesis, University of Mansoura.
- El-Beialy, S. Y., Edwards, K. J., El-Mahmoudi, A. S., 2001. Geophysical and palynological investigations of the Tell El Daba'a archaeological site, Nile Delta, Egypt. *Antiquity* 75 (290), 735–744.
- El-Hinnawi, E. E., El-Shahat, A., 1969. Ore-microscopic studies on opaque minerals from sand islet in the Nile Delta. *Chemie der Erde* 28, 23–29.
- El-Mahmoudi, A. S., El-Gamili, M. M., El-Shahat, A., Farid, A., 2005. Geoelectric resistivity contribution to the Late Quaternary geology of the north eastern corner of the Nile Delta, Egypt. In: *The Sixth Annual U.A.E. University Research Conference*, College of Science. pp. 15–35.
- El-Mahmoudi, A. S., Gabr, A., 2009. Geophysical surveys to investigate the relation between the Quaternary Nile channels and the Messinian Nile canyon at East Nile Delta, Egypt. *Arabic Journal of Geosciences* 2 (1), 53–67.
- El-Shahat, A., El-Mahmoudi, A. S., El-Gamili, M. M., Farid, A., 1999. Lithostratigraphy of the Late Quaternary sediments in the northern Nile Delta. In: Zaghloul, Z. M., El-Gamal, M. M. (Eds.), *Deltas Modern & Ancient: First International Symposium on the Deltas*. Mansoura University, Mansoura, pp. 1–20.
- El-Shahat, A., Ghazala, H., Wilson, P., Belal, Z., 2005. Lithofacies of the Upper Quaternary sequence of Sa el-Hagar area, Gharbiya Governorate, Nile Delta, Egypt. *Mansoura Journal of Geology & Geophysics* 32, 97–120.
- Flaux, C., 2012. Holocene Palaeo-environments of the Maryut lagoon in the NW Nile Delta, Egypt. Ph.D. thesis, Université Aix-Marseille.
- Flaux, C., Claude, C., Marriner, N., Morhange, C., 2013. A 7500-year strontium isotope record from the northwestern Nile Delta (Maryut lagoon, Egypt). *Quaternary Science Reviews* 78, 22–33.
- Flaux, C., El-Assal, M., Marriner, N., Morhange, C., Rouchy, J.-M., Soulié-Märsche, I., Torab, M., 2012. Environmental changes in the Maryut lagoon (northwestern Nile Delta) during the last 2000 years. *Journal of Archaeological Science* 39 (12), 3493–3504.
- Flaux, C., Marriner, N., El-Assal, M., Kaniewski, D., Morhange, C., 2017. Late Holocene erosion of the Canopic promontory (Nile Delta, Egypt). *Marine Geology* 385, 56–67.
- Flaux, C., Morhange, C., Marriner, N., Rouchy, J.-M., 2011. Bilan hydrologique et biosédimentaire de la lagune du Maryût (delta du Nil, Egypte) entre 8000 et 3200 ans cal. B.P. *Géomorphologie* 17 (3), 261–278.
- Fleitmann, D., Burns, S. J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., Matter, A., 2003. Holocene forcing of the Indian

- monsoon recorded in a stalagmite from southern Oman. *Science* 300 (5626), 1737–1739.
- Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate field sites. *Earth and Planetary Science Letters* 163 (1), 327–342.
- Fourtau, R., 1915. Contribution à l'étude des dépôts nilotiques. In: *Mémoires de l'Institut Égyptien*. Vol. 8. L'Institut Égyptien, Cairo, pp. 57–94.
- Gamal, M. A., 2013. Truthfulness of the existence of the Pelusium megashear fault system, east of Cairo, Egypt. *International Journal of Geosciences* 4 (1), 212–227.
- Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. *Quaternary Science Reviews* 19 (1-5), 189–211.
- Ghazala, H., El-Shahat, A., Abd el Raouf, O., Wilson, P., Belal, Z., 2005. Geophysical investigations around Sa el-Hagar archaeological site, Gharbiya Governorate, Nile Delta, Egypt. *Mansoura Journal of Geology & Geophysics* 32, 121–138.
- Giosan, L., Clift, P. D., Alizai, A., Macklin, M. G., Durcan, J. A., Duller, G. A. T., Fuller, D. Q., Constantinescu, S., Filip, F., Stevens, T., Tabrez, A. R., Gangal, K., Adhikari, R., Van Laningham, S., Syvitski, J. P. M., 2012. Fluvial landscapes of the Harappan civilization. *PNAS* 109 (26), 1688–1694.
- URL <http://search.ebscohost.com/login.aspx?direct=true&db=edselc&AN=edselc.2-52.0-84862992518&jsite=eds-live>
- Goodfriend, G. A., Stanley, D. J., 1999. Rapid strand-plain accretion in the northeastern Nile Delta in the 9th century A.D. and the demise of the port of Pelusium. *Geology* 27 (2), 147–150.
- Hamdan, M. A., 2003. Late Quaternary geology and geoarchaeology of Kafr Hassan Dawood, East Delta. In: Hawass, Z., Pinch Brock, L. (Eds.), *Egyptology at the Dawn of the Twenty-First Century: Proceedings of the Eighth International Congress of Egyptologists*, Cairo, 2000. Vol. 1. The American University in Cairo Press, Cairo, pp. 221–228.
- Hamroush, H., 1987. Geoarchaeology of the Kom el-Hisn area: tracing ancient sites in the western Nile Delta, Egypt. Tech. rep., Department of Geology, Cairo University, Cairo.
- Hartung, U., 2008. Recent investigations at Tell el-Fara'in/Buto. In: Midant-Reynes, B., Tristant, Y. (Eds.), *Egypt at its Origins 2: Proceedings of the international conference "Origin of the State. Predynastic and Early Dynastic Egypt"*, Toulouse, 5th – 8th September 2005. Peeters, Leuven, pp. 1195–1219.
- Hassan, F. A., 1997. The dynamics of a riverine civilization: a geoarchaeological perspective on the Nile Valley, Egypt. *World Archaeology* 29 (1), 51–74.
- Hassan, F. A., 2009. Human agency, climate change and culture: an archaeological perspective. In: *Anthropology and Climate Change: From encounters to actions*. Left Coast Press, Walnut Creek, pp. 39–69.
- Hassan, F. A., 2010. Climate change, Nile floods and riparia. In: Hermon, E. (Ed.), *Riparia dans l'Empire Romain: pour la définition du concept*. John and Erica Hedges Ltd, Oxford, pp. 1–20.
- Hennekam, R., Donders, Timme, H., Zwiep, K., de Lange, G. J., 2015. Integral view of Holocene precipitation and vegetation changes in the Nile catchment area as inferred from its delta sediments. *Quaternary Science Reviews* 130, 189–199.
- Honegger, M., Williams, M., 2015. Human occupations and environmental changes in the Nile Valley during the Holocene: The case of Kerma in Upper Nubia (northern Sudan). *Quaternary Science Reviews* 130, 141–154.
- Hughes, E., 2008. Charting Ancient Waterways with the British Museum Mission to Kom Firin. Unpublished MSci Thesis, Dept. of Earth Sciences, University of Cambridge.
- Hussein, H. M., Abou Elenean, K. M., Marzouk, I. A., Korrat, I. M., Abu El-Nader, I. F., Ghazala, H., El-Gabry, M. N., 2013. Present-day tectonic stress regime in Egypt and surrounding area based on inversion of earthquake focal mechanisms. *Journal of African Earth Sciences* 81, 1–15.
- Jarvis, A., Reuter, H. A., Nelson, A., Guevara, E., 2008. Hole-filled seamless SRTM data V4. International Centre for Tropical Agriculture (CIAT). <http://srtm.csi.cgiar.org> (last accessed February 2017).
- Jerolmack, D. J., 2009. Conceptual framework for assessing the response of delta channel networks to Holocene sea level rise. *Quaternary Science Reviews* 28 (17-18), 1786–1800.
- Jerolmack, D. J., Mohrig, D., 2007. Conditions for branching in depositional rivers. *Geology* 35 (5), 463–466.
- Jotheri, J., Allen, M. B., Wilkinson, T. J., 2016. Holocene avulsions of the Euphrates river in the Najaf area of western Mesopotamia: impacts on human settlement patterns. *Geoarchaeology* 31 (3), 175–193.
- Judd, J. W., 1885. Report on a series of specimens of the deposits of the Nile Delta, obtained by the recent boring operations. *Proceedings of the Royal Society of London* 39 (239-241), 213–227.
- Judd, J. W., 1897. Second report on a series of specimens of the deposits of the Nile Delta, obtained by the recent boring operations. *Proceedings of the Royal Society of London* 61 (369-377), 32–40.
- Kemp, B. J., 2006. *Ancient Egypt: Anatomy of a civilisation*, second edition. Routledge, London.
- Kholief, M. M., Hilmy, E., Shahat, A., 1969. Geological and mineralogical studies of some sand deposits in the Nile Delta, U.A.R. *Journal of Sedimentary Petrology* 39 (4), 1520–1529.
- Kirby, C. J., Orel, S. E., Smith, S. T., 1998. Preliminary report on the survey of Kom el-Hisn. *Journal of Egyptian Archaeology* 84, 23–43.
- Kraus, M. J., 1996. Avulsion deposits in Lower Eocene alluvial rocks, Bighorn Basin, Wyoming. *Journal of Sedimentary Research* 66 (2), 354–363.
- Kraus, M. J., Aslan, A., 1993. Eocene hydromorphic paleosols: significance for interpreting ancient floodplain processes. *Journal of Sedimentary Petrology* 63 (3), 453–463.
- Krom, M. D., Stanley, D. J., Clift, R. A., Woodward, J. C., 2002. Nile River sediment fluctuations over the past 7000 yr and their key role in sapropel development. *Geology* 30 (1), 71–74.
- Kröpelin, S., Verschuren, D., Lézine, A. M., Eggermont, H., Cocquyt, C., Francus, P., Cazet, J. P., Fagot, M., Rumes, B., Russell, J. M., Darius, F., Conley, D. J., Schuster, M., von Suchbalek, H., Engstrom, D. R., 2008. Climate-driven ecosystem succession in the Sahara: the past 6000 years. *Science* 320 (5877), 765–768.
- Krzyzaniak, L., 1992. Again on the earliest settlement at Minshat Abu Omar. In: van den Brink, E. C. M. (Ed.), *The Nile Delta in Transition: 4th-3rd millennium BC*. IES, Tel Aviv, pp. 151–155.
- Krzyzaniak, L., 1993. New data on the Late Prehistoric settlement at Minshat Abu Omar (Eastern Nile Delta). In: Krzyzaniak, L., Kobusiewicz, M., Alexander, J. (Eds.), *Environmental Change and Human Culture in the Nile Basin and Northern Africa until the 2nd millennium B.C*. Poznań Archaeological Museum, Poznań, pp. 321–325.
- Lemoine, F. G., Kenyon, S. C., Factor, J. K., Trimmer, R. G., Pavlis, N. K., Chinn, D. S., Cox, C., Klosko, S. M., Luthcke, S. B., Torrence, M. H., Wang, Y. M., Williamson, R. G., Pavlis, E. C., Rapp, R. H., Olson, T. R., 1998. The development of the joint NASA GSFC and NIMA geopotential model EGM96. Tech. rep., NASA Goddard Space Flight Center, Greenbelt.
- Leonard, A., 1997. *Ancient Naukratis: Excavations at a Greek emporium in Egypt I: The excavations at Kom Geif*. American Schools of Oriental Research, Boston.
- Leroy, S. A. G., 1992. Palynological evidence of *Azolla nilotica* Dec. in recent Holocene of the eastern Nile Delta and palaeoenvironment. *Vegetation History and Archaeobotany* 1 (1), 43–52.
- Lutley, K., Bunbury, J. M., 2008. The Nile on the move. *Egyptian Archaeology* 32, 3–5.
- Macklin, M. G., Lewin, J., 2015. The rivers of civilization. *Quaternary Science Reviews* 114, 228–244.
- Macklin, M. G., Toonen, W. H. J., Woodward, J. C., Williams, M. A. J., Flaux, C., Marriner, N., Nicoll, K., Verstraeten, G., Spencer, N., Welsby, D., 2015. A new model of river dynamics, hydroclimatic change and human settlement in the Nile Valley derived from meta-analysis of the Holocene fluvial archive. *Quaternary Science Reviews* 130, 109–123.

- Macklin, M. G., Woodward, J. C., Welsby, D., Duller, G. A. T., Williams, F. M., Williams, M. A. J., 2013. Reach-scale river dynamics moderate the impact of rapid Holocene climate change on floodwater farming in the desert Nile. *Geology* 41 (6), 695–698.
- Maczyńska, A., 2011. The Lower Egyptian-Naqada transition: a view from Tell el-Farkha. In: Friedman, R., Fiske, P. N. (Eds.), *Egypt at its Origins 3: Proceedings of the third international conference “Origin of the State. Predynastic and Early Dynastic Egypt”*, London, 27th July – 1st August 2008. Peeters, Leuven, pp. 879–908.
- Marriner, N., Flaux, C., Kaniewski, D., Morhange, C., Leduc, G., Moron, V., Chen, Z., Gasse, F., Empereur, J.-Y., Stanley, D. J., 2012a. ITCZ and ENSO-like pacing of Nile Delta hydrogeomorphology during the Holocene. *Quaternary Science Reviews* 45, 73–84.
- Marriner, N., Flaux, C., Morhange, C., Kaniewski, D., 2012b. Nile Delta’s sinking past: quantifiable links with Holocene compaction and climate-driven changes in sediment supply? *Geology* 40 (12), 1083–1086.
- Marriner, N., Flaux, C., Morhange, C., Stanley, D. J., 2013. Tracking Nile Delta vulnerability to Holocene change. *PLOS One* 8 (7), 1–8.
- Marshall, M. H., Lamb, H. F., Huws, D., Davies, S. J., Bates, R., Bloemendal, J., Boyle, J., Leng, M. J., Umer, M., Bryant, C., 2011. Late Pleistocene and Holocene drought events at Lake Tana, the source of the Blue Nile. *Global and Planetary Change* 78 (3), 147–161.
- Mohrig, D., Heller, P. L., Paola, C., Lyons, W. J., 2000. Interpreting avulsion processes from ancient alluvial sequences: Guadalope-Matarranya system (northern Spain) and Watsch Formation (western Colorado). *GSA Bulletin* 112 (12), 1787–1803.
- Moshier, S. O., El-Kalani, A., 2008. Late Bronze Age paleogeography along the Ancient Ways of Horus in northwest Sinai, Egypt. *Geoarchaeology* 23 (4), 450–473.
- NASA, 1998. NGA/NASA EGM96, N=M=360 Earth Gravitational Model (F477.exe). <http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm96/egm96.html> (last accessed February 2017).
- NASA, 2008. EGM2008 GIS Data. http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_gis.html (last accessed February 2017).
- Neev, D., 1975. Tectonic evolution of the Middle East and the Levantine Basin (easternmost Mediterranean). *Geology* 3 (12), 683–686.
- Neev, D., 1977. The Pelusium Line, a major transcontinental shear. *Tectonophysics* 38 (3–4), T1–T8.
- Pavlis, N. K., Holmes, S. A., Kenyon, S. C., Factor, J. K., 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research: Solid Earth* 117 (B4), 1–38.
- Pawlikowski, M., 2006. *Geology, sedimentology and mineralogy*. Archeologia 17, 120–128.
- Pawlikowski, M., Wasilewski, M., 2012. *Geology, sedimentology and mineralogy of the Tell el Farkha site, the eastern Nile Delta, Egypt*. In: Chłodnicki, M., Ciałowicz, K. M., Maczyńska, A. (Eds.), *Tell el-Farkha I: Excavations 1998–2011*. Poznań Archaeological Museum, Poznań, pp. 375–382.
- Pennington, B. T., Bunbury, J. M., Hovius, N., 2016. Emergence of civilisation, changes in fluvio-deltaic styles and nutrient redistribution forced by Holocene sea-level rise. *Geoarchaeology* 31 (3), 194–210.
- Pennington, B. T., Thomas, R. I., 2016. Paleoenvironmental surveys at Naukratis and the Canopic branch of the Nile. *Journal of Archaeological Science: Reports* 7, 180–188.
- Phillips, J. D., 2011. Universal and local controls of avulsions in southeast Texas rivers. *Geomorphology* 130 (1), 17–28.
- Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Cheng, H., Lawrence, R. E., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haffidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., van der Plicht, J., 2013. IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon* 55 (4), 1869–1887.
- Revel, M., Ducassou, E., Skonieczny, C., Colin, C., Bastian, L., Bosch, D., Migeon, S., Mascle, J., 2015. 20,000 years of Nile River dynamics and environmental changes in the Nile catchment area as inferred from Nile upper continental slope sediments. *Quaternary Science Reviews* 130, 200–221.
- RIGW, 1985. *Research Institute for Groundwater Water Resources Database*. Department of Irrigation, Cairo.
- Rizzini, A., Vezzani, F., Cococetta, V., Milad, G., 1978. Stratigraphy and sedimentation of a Neogene-Quaternary section in the Nile Delta area. *Marine Geology* 27 (3–4), 327–348.
- Rockware, 2008. *Rockworks 15 Documentation*. Rockware, Golden.
- Rowland, J., Edinborough, K., Philipps, R., El-Senussi, A., 2009. The Delta Survey, Minufiyeh Province, 2008–9. *Journal of Egyptian Archaeology* 95, 35–49.
- Rowland, J. M., 2007. The Delta Survey: Minufiyeh Province, 2006–7. *Journal of Egyptian Archaeology* 93, 65–77.
- Rowland, J. M., Hamdan, M. A., 2012. The Holocene evolution of the Quesna turtle-back: geological evolution and archaeological relationships within the Nile Delta. In: Kabaciński, J., Chłodnicki, M., Kobusiewicz, M. (Eds.), *Prehistory of Northeastern Africa: New ideas and discoveries*. Poznań Archaeological Museum, Poznań, pp. 11–24.
- Saad, S. I., Sami, S., 1967. Studies of pollen and spores content of Nile Delta deposits (Berenbal region). *Pollen et spores* 9 (3), 467–503.
- Said, R., 1971. Explanatory notes to accompany the geological map of Egypt. Tech. Rep. 56, Geological Survey of Egypt, Cairo.
- Said, R., 1981. *The Geological Evolution of the River Nile*. Springer-Verlag, New York.
- Said, R., 1992. The geological history of the Nile Delta. In: van den Brink, E. C. M. (Ed.), *The Nile Delta in Transition: 4th–3rd millennium BC*. IES, Tel Aviv, pp. 259–267.
- Said, R., 1993. *The Nile River: Geology, hydrology and utilization*. Pergamon Press, New York.
- Sandford, K. S., Arkell, W. J., 1939. *Paleolithic Man and the Nile Valley in Lower Egypt with some notes upon a part of the Red Sea Littoral: A study of the regions during Pliocene and Pleistocene times*. University of Chicago Press, Chicago.
- Schiestl, R., 2010. Second report on the regional survey in the governorate of Kafr esh-Sheikh, season Autumn 2010. Unpublished report.
- Schiestl, R., 2012. Report on the regional survey in the governorate of Kafr esh-Sheikh, spring and autumn 2012. Unpublished report.
- Schiestl, R., Ginau, A., 2015. Report on the season 2015 of the regional survey around Buto (Tell el-Fara’in), governorate Kafr esh-Shaikh. Unpublished report.
- Schiestl, R., Ginau, A., Rosenow, D., 2014. Report on the 2014 season of the regional survey in the governorate of Kafr esh-Sheikh. Unpublished report.
- Schlumberger, 1995. Well evaluation conference, Egypt. <http://www.slb.com/resources/publications/roc/egypt95.aspx> (last accessed February 2017).
- Sestini, G., 1976. Geomorphology of the Nile Delta. In: *Proceedings of the Seminar on Nile Delta Sedimentology*. UNESCO/ASRT/UNDP, Alexandria, pp. 12–24.
- Sewuster, R. J. E., van Wesemael, B., 1987. Tracing ancient river courses in the eastern Nile Delta. Tech. Rep. 30, Laboratory of Physical Geography and Soil Science, University of Amsterdam, Amsterdam.
- Shanahan, T. M., McKay, N. P., Hughen, K. A., Overpeck, J. T., Otto-Bliesner, B., Heil, C. W., King, J., Scholz, C. A., Peck, J., 2015. The time-transgressive termination of the African Humid Period. *Nature Geoscience* 8 (2), 140–144.
- Sivan, D., Lambeck, K., Toueg, R., Raban, A., Porath, Y., Shirman, B., 2004. Ancient coastal wells of Caesarea Maritima, Israel, an indicator for relative sea level changes during the last 2000 years. *Earth and Planetary Science Letters* 222 (1), 315–330.
- Sivan, D., Wdowinski, S., Lambeck, K., Galili, E., Raban, A., 2001. Holocene sea-level changes along the Mediterranean coast of Is-

- rael, based on archaeological observations and numerical model. *Palaeogeography, Palaeoclimatology, Palaeoecology* 167 (1-2), 101–117.
- Slingerland, R., Smith, N. D., 2004. River avulsions and their deposits. *Annual Reviews of Earth and Planetary Sciences* 32, 257–285.
- Smith, N. D., Cross, T. A., Dufficy, J. P., Clough, S. R., 1989. Anatomy of an avulsion. *Sedimentology* 36 (1), 1–24.
- Smith, N. D., Pérez-Arlucea, M., 1994. Fine-grained splay deposition in the avulsion belt of the lower Saskatchewan river, Canada. *Journal of Sedimentary Petrology* 64 (2), 159–168.
- Sneh, A., Weissbrod, T., Ehrlich, A., Moshkovitz, S., Rosenfield, A., 1986. Holocene evolution of the northeastern corner of the Nile Delta. *Quaternary Research* 26 (2), 194–206.
- Spencer, N., 2007. The British Museum expedition to Kom Firin: report on the 2007 Season. http://www.britishmuseum.org/PDF/Kom_Firin_2007.pdf (last accessed February 2017).
- Stanley, D. J., 1988. Subsidence in the northeastern Nile delta: rapid rates, possible causes, and consequences. *Science* 240 (4851), 495–500.
- Stanley, D. J., 1990. Recent subsidence and northeast tilting of the Nile Delta. *Marine Geology* 94 (1-2), 147–154.
- Stanley, D. J., Bernhardt, C. E., 2010. Alexandria's eastern harbor, Egypt: pollen, microscopic charcoal, and the transition from natural to human-modified basin. *Journal of Coastal Research* 26 (1), 67–79.
- Stanley, D. J., Chen, Z., 1991. Distinguishing sand facies in the Nile Delta, Egypt, by stained grain and compositional component analysis. *Journal of Coastal Research* 7 (3), 863–877.
- Stanley, D. J., Clemente, P. L., 2014. Clay distributions, grain sizes, sediment thicknesses, and compaction rates to interpret subsidence in Egypt's northern Nile Delta. *Journal of Coastal Research* 30 (1), 88–101.
- Stanley, D. J., Mcree Jr, J. E., Waldron, J. C., 1996. Nile Delta Drill Core and Sample Database for 1985–1994: Mediterranean Basin (MEDIBA) program. Smithsonian Institution Press, Washington, D.C.
- Stanley, D. J., Warne, A. G., 1993a. Nile Delta: recent geological evolution and human impact. *Science* 260 (5108), 628–634.
- Stanley, D. J., Warne, A. G., 1993b. Sea level and initiation of Predynastic culture in the Nile Delta. *Nature* 363 (6428), 435–438.
- Stanley, D. J., Warne, A. G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. *Science* 265 (5169), 228–231.
- Stanley, D. J., Warne, A. G., 1997. Holocene sea level changes and early human utilization of deltas. *GSA Today* 7 (12), 1–7.
- Stanley, D. J., Warne, A. G., 1998. Nile Delta in its destruction phase. *Journal of Coastal Research* 14 (3), 794–825.
- Stanley, D. J., Warne, A. G., Davis, H. R., Bernasconi, M. P., Chen, Z., 1992. Nile Delta: the Late Quaternary north-central Nile Delta from Manzala to Burullus Lagoons, Egypt. *National Geographic Research and Exploration* 8 (1), 22–51.
- Stuiver, J. D., Kra, R. S., 1986. Calibration issue, *Proceedings of the 12th International 14C conference. Radiocarbon* 28 (2B), 805–1030.
- Summerhayes, C. P., Sestini, G., Misdorp, R., 1978. Nile Delta: nature and evolution of continental shelf sediments. *Marine Geology* 27 (1-2), 43–65.
- Tassie, G. J., 2014. Prehistoric Egypt: Socioeconomic transformations in North-east Africa from the Last Glacial Maximum to the Neolithic, 24,000–4,000BC. Golden House Publications, London.
- Tawadros, E., 2011. *Geology of North Africa*. CRC Press, Boca Raton.
- Tingay, M., Bentham, P., De Feyter, A., Kellner, A., 2011. Present-day stress-field rotations associated with evaporites in the offshore Nile Delta. *GSA Bulletin* 123 (5-6), 1171–1180.
- Toonen, W. H. J., Graham, A., Pennington, B. T., Hunter, M. A., Strutt, K. D., Barker, D. S., Masson-Berghoff, A., Emery, V. L., in press. Holocene fluvial history of the Nile floodplain at ancient Thebes (Luxor, Egypt) and its relation with cultural dynamics and basin-wide hydroclimatic variability. *Geoarchaeology*.
- Törnqvist, T. E., 1993. *Fluvial Sedimentary Geology and Chronology of the Holocene Rhine-Meuse delta*, The Netherlands. Ph.D. thesis, Universiteit Utrecht.
- Trampier, J. R., 2014. *Landscape Archaeology of the Western Nile Delta*. Lockwood Press, Atlanta.
- Trampier, J. R., Toonen, W. H. J., Simony, A., Starbird, J., 2013. Missing Koms and abandoned channels: the potential of regional survey in the western Nile Delta landscape. *Journal of Egyptian Archaeology* 99, 217–240.
- Tristant, Y., 2006. *L'Occupation Humaine dans le Delta du Nil au 5e et 4e Millénaires: Approche Géo-archéologique à partir de la Région de Samara (Delta Oriental)*. Ph.D. thesis, École des hautes études en sciences sociales.
- Tristant, Y., De Dapper, M., 2009. Predynastic man and landscape in the Samara area. In: De Dapper, M., Vermeulen, F. (Eds.), *Ol'Man River: Geo-archaeological aspects of rivers and river plains*. Academia Press, Ghent, pp. 601–617.
- Tristant, Y., De Dapper, M., Aussel, S., Midant-Reynes, B., 2011. Cultural and natural environment in the eastern Nile Delta: a geoarchaeological project at Tell el-Iswid (Nile Delta). In: Friedman, R., Fiske, P. N. (Eds.), *Egypt at its Origins 3: Proceedings of the third international conference "Origin of the State. Predynastic and Early Dynastic Egypt"*, London, 27th July – 1st August 2008. Peeters, Leuven, pp. 171–173.
- Tristant, Y., De Dapper, M., Midant-Reynes, B., 2007. Recherches géo-archéologiques sur le site pré- et protodynastique de Kôm el-Khilgan (Delta du Nil): résultats préliminaires des campagnes de prospection 2002–2004. In: Goyon, J. C., Cardin, C., Garrel, J. F., Zaki, G. (Eds.), *Proceedings of the Ninth International Congress of Egyptologists. Vol. 2*. Peeters, Leuven, pp. 1841–1850.
- Tristant, Y., De Dapper, M., Midant-Reynes, B., 2008. Human occupation of the Nile Delta during pre-and early dynastic times. A View from Kom el-Khilgan. In: Midant-Reynes, B., Tristant, Y. (Eds.), *Egypt at its Origins 2: Proceedings of the international conference "Origin of the State. Predynastic and Early Dynastic Egypt"*, Toulouse, 5th – 8th September 2005. Peeters, Leuven, pp. 463–482.
- Tronchère, H., Goiran, J.-P., Schmitt, L., Preusser, F., Bietak, M., Forstner-Müller, I., Callot, Y., 2012. Geoarchaeology of an ancient fluvial harbour: Avaris and the Pelusiac branch (Nile River, Egypt). *Géomorphologie* 18 (1), 23–36.
- Tronchère, H., Salomon, F., Callot, Y., Goiran, J.-P., Schmitt, L., Forstner-Müller, I., Bietak, M., 2009. Geoarchaeology of Avaris: first results. *Ägypten und Levante* 28, 327–340.
- van den Brink, E. C. M., 1992. Preliminary report on the excavations at Tell Ibrahim Awad, seasons 1988–1990. In: van den Brink, E. C. M. (Ed.), *The Nile Delta in Transition: 4th–3rd millennium BC*. IES, Tel Aviv, pp. 43–68.
- van Wesemael, B., Dirks, P., 1986. The relation between the natural landscape and the spatial distribution of archaeological remains. Tech. Rep. 24, Laboratory of Physical Geography and Soil Science, University of Amsterdam, Amsterdam.
- Vermeersch, P. M., Van Neer, W., 2015. Nile behaviour and Late Palaeolithic humans in Upper Egypt during the Late Pleistocene. *Quaternary Science Reviews* 130, 155–167.
- Villas, C., 1996. Geological investigations. In: Coulson, W. D. (Ed.), *Ancient Naukratis II.1: The survey at Naukratis*. Oxbow Books, Oxford, pp. 163–175.
- von der Way, T., 1997. Tell el Fara'in - Buto I. Ergebnisse zum frühen Kontext. Kampagnen der Jahre 1983–1989. Archäologische Veröffentlichungen Deutsches Archäologisches Institut Kairo, Mainz.
- Warne, A. G., Stanley, D. J., 1993a. Archaeology to refine Holocene subsidence rates along the Nile Delta margin, Egypt. *Geology* 21 (8), 715–718.
- Warne, A. G., Stanley, D. J., 1993b. Late Quaternary evolution of the northwest Nile Delta and adjacent coast in the Alexandria region, Egypt. *Journal of Coastal Research* 9 (1), 26–64.
- Weerts, H. J. T., 1996. *Complex Confining Layers: Architecture and hydraulic properties of Holocene and Late Weichselian deposits in the fluvial Rhine-Meuse delta*, The Netherlands. Ph.D. thesis,

- Universiteit Utrecht.
- Wenke, R. J., Buck, P. E., Hamroush, H. A., Kobusiewicz, M., Kroeper, K., Redding, R. W., 1988. Kom el-Hisn: excavation of an Old Kingdom settlement in the Egyptian Delta. *Journal of the American Research Center in Egypt* 25, 5–34.
- Williams, M. A. J., 2009. Late Pleistocene and Holocene environments in the Nile basin. *Global and Planetary Change* 69 (1), 1–15.
- Williams, M. A. J., Usai, D., Salvatori, S., Williams, F. M., Zerboni, A., Maritan, L., Linseele, V., 2015. Late Quaternary environments and prehistoric occupation in the lower White Nile Valley, central Sudan. *Quaternary Science Reviews* 130, 72–88.
- Willis, B. J., Behrensmeyer, A. K., 1994. Architecture of Miocene overbank deposits in northern Pakistan. *Journal of Sedimentary Research* 64 (1), 60–67.
- Wilson, P., 2006a. Prehistoric settlement in the western delta: A regional and local view from Sais (Sa el-Hagar). *Journal of Egyptian Archaeology* 92, 75–126.
- Wilson, P., 2006b. The Survey of Sais (Sa el-Hagar), 1997–2002. Egypt Exploration Society, London.
- Wilson, P., 2007. The Western Delta Regional Survey. <https://community.dur.ac.uk/penelope.wilson/Delta/Survey.html> (last accessed February 2017).
- Wilson, P., 2010. Settlement connections in the Canopic region. In: Robinson, D., Wilson, A. (Eds.), *Alexandria and the North-Western Delta*. Oxford Centre for Maritime Archaeology, Oxford, pp. 111–126.
- Wilson, P., 2011. Ramsis: ancient memory, archaeology and the western Delta. In: Collier, M., Snape, S. (Eds.), *Ramesside Studies in Honour of K. A. Kitchen*. Rutherford Press, Bolton, pp. 533–540.
- Wilson, P., Gilbert, G., Tassie, G., 2014. Sais II: The prehistoric period. Egypt Exploration Society, London.
- Wilson, P., Grigoropoulos, D., 2009. The West Nile Delta Regional Survey, Beheira and Kafr el-Sheikh provinces. Egypt Exploration Society, London.
- Woodward, J., Macklin, M., Fielding, L., Miller, I., Spencer, N., Welsby, D., Williams, M., 2015. Shifting sediment sources in the world's longest river: a strontium isotope record for the Holocene Nile. *Quaternary Science Reviews* 130, 124–140.
- Woodward, J. C., Welsby, D., Macklin, M. G., 2001. The Holocene fluvial sedimentary record and alluvial geoarchaeology in the Nile Valley of northern Sudan. In: Woodward, J. C., Maddy, D., Macklin, M. G. (Eds.), *River Basin Sediment Systems: Archives of environmental change*. A. A. Balkema, Lisse, pp. 327–355.
- Wunderlich, J., 1988. Investigations on the development of the western Nile Delta in Holocene times. In: van den Brink, E. C. M. (Ed.), *The Archaeology of the Nile Delta: Problems and priorities*. Netherlands Foundation for Archaeological Research in Egypt, Amsterdam, pp. 251–257.
- Wunderlich, J., 1989. Untersuchungen zur Entwicklung des westlichen Nildeltas im Holozän. Ph.D. thesis, Philipps-Universität Marburg.
- Wunderlich, J., 1993. The natural conditions for Pre-and Early Dynastic settlement in the western Nile Delta around Tell el-Fara'in, Buto. In: Krzyzaniak, L., Kobusiewicz, M., Alexander, J. (Eds.), *Environmental Change and Human Culture in the Nile Basin and Northern Africa until the 2nd millennium B.C.* Poznań Archaeological Museum, Poznań, pp. 259–266.
- Wunderlich, J., Andres, W., 1991. Late Pleistocene and Holocene evolution of the western Nile Delta and implications for its future development. In: Brückner, H., Radtke, U. (Eds.), *Von der Nordsee bis zum Indischen Ozean*. Steiner, Stuttgart, pp. 105–120.
- Wunderlich, J., Von der Way, T., Schmidt, K., 1989. Neue Fundstellen der Buto-Maadi-Kultur bei Ezbet el-Qerdahi. *Mitteilungen des Deutschen Archäologischen Instituts. Abteilung Kairo* 45, 309–318.
- Zaghloul, Z. M., El-Shahat, A., Hegab, O., Kora, M. A. M., 1980. Mineralogy of the Tertiary-Quaternary subsurface sediments, west Nile Delta area, Egypt. *Egyptian Journal of Geology* 24, 177–188.
- Zalat, A. A., 1995. Diatoms from the Quaternary sediments of the Nile Delta, Egypt, and their palaeoecological significance. *Journal of African Earth Sciences* 20 (2), 133–150.

Supplementary Information Follows:

TABLE 1: Cores included in the lithostratigraphic database. H1–3 refers to the degree of error in the horizontal resolution of the borehole; V1–3 similarly for the vertical error; S1–3 the degree of stratigraphic confidence (see below).

Name	No. of cores	H1	H2	H3	V1	V2	V3	S1	S2	S3	References (see below)
AUSE	523	0	131	392	517	6	0	523	0	0	¹
Sais	276	272	4	0	147	66	63	261	15	0	²
SOE	234	0	180	54	230	0	4	71	125	38	³
BRS	97	22	73	2	85	5	7	95	2	0	⁴
MEDIBA	87	0	83	4	0	85	2	79	4	4	⁵
WDLP	63	63	0	0	0	63	0	63	0	0	⁶
Kom Geif	61	61	0	0	61	0	0	61	0	0	⁷
WDRS	44	44	0	0	32	0	12	44	0	0	⁸
Isolated municipal & other	55	0	15	40	29	0	26	53	2	0	⁹
MAS	40	38	2	0	0	0	40	37	3	0	¹⁰
Kom el-Hisn	27	0	26	1	27	0	0	27	0	0	¹¹
KA/KW	26	26	0	0	0	26	0	26	0	0	¹²
Tell Mutubis	25	25	0	0	0	24	1	25	0	0	¹³
Tell el-Dab ^c a	24	0	24	0	12	0	12	24	0	0	¹⁴
MUWDS	17	10	7	0	15	0	2	17	0	0	¹⁵
MAO	15	9	6	0	15	0	0	15	0	0	¹⁶
Kom Firin	11	11	0	0	11	0	0	11	0	0	¹⁷

¹de Wit, (1993); de Wit and van Stralen, (1988b, 1988a); Sewuster and van Wesemael, (1987); van Wesemael and Dirks, (1986)

²El-Shahat et al. (2005); Wilson (2006b,a); Wilson et al. (2014); unpublished cores (Wilson)

³Attia (1954); Fourtau (1915); Judd (1897, 1885)

⁴Andres and Wunderlich, 1986; Hartung, 2008; Schiestl, 2012, 2010; Schiestl and Ginau, 2015; Schiestl et al., 2014; von der Way, 1997, p. 42; Wunderlich, 1993, 1989, 1988; Wunderlich and Andres, 1991; Wunderlich et al., 1989

⁵Stanley et al. (1996); Coutellier and Stanley (1987); Arbouille and Stanley (1991); Chen et al. (1992); Stanley et al. (1992)

⁶Trampier (2014); Trampier et al. (2013)

⁷Coulson (1996); Leonard (1997); Pennington and Thomas (2016); Villas (1996); unpublished cores (Pennington)

⁸Wilson (2007); Wilson and Grigoropoulos (2009); unpublished cores (Wilson)

⁹El-Awady (2009); El-Mahmoudi and Gabr (2009); El-Mahmoudi et al. (2005); El-Shahat et al. (2005, 1999); Hamroush (1987); RIGW (1985); Said (1981); Zalat (1995)

¹⁰Rowland (2007); Rowland and Hamdan (2012); Rowland et al. (2009); unpublished cores (Rowland)

¹¹Buck (1990); Hamroush (1987); Kirby et al. (1998); Wenke et al. (1988)

¹²Unpublished cores (Pennington)

¹³Unpublished cores (Pennington; Wilson)

¹⁴Bietak (1975); Dorner (1999, 1994); El-Beialy et al. (2001); Tronchère et al. (2012, 2009)

¹⁵El-Awady (2009)

¹⁶Andres and Wunderlich (1992, 1991); Krzyzaniak, (1993, 1992)

¹⁷Hughes (2008); Spencer (2007)

TABLE 1: Continued from previous page

Survey	No. of cores	H1	H2	H3	V1	V2	V3	S1	S2	S3	References (see below)
Tell el-Iswid S	6	6	0	0	6	0	0	6	0	0	¹⁸
KK/TS	4	4	0	0	3	0	1	4	0	0	¹⁹
KHD	3	0	3	0	0	0	3	3	0	0	²⁰
Tell el-Farkha	2	2	0	0	2	0	0	2	0	0	²¹

For each core, the potential error in each of the three data elements (horizontal position; vertical elevation; stratigraphic assignment) was estimated on a 1–3 scale. For the error in horizontal position, a value of “1” (low) indicated a potential error of <5m; a value of “2” (medium) corresponded to a potential error of 5–250m; a value of “3” (high) indicated an error of 250m–2.5km (usually 250–500m). For the error in vertical elevation, a value of “1” indicated a potential error of ± 0.15 m; a value of “2” corresponded to a potential error of ± 0.5 m; a value of “3” indicated an error greater than this. The error in stratigraphic assignment was estimated qualitatively.

In some cases, particular surveys have also undertaken many more boreholes than were input. In the majority of cases, the extra boreholes were not included simply because the data has not yet been published. In other cases, where a large number of boreholes have been undertaken in a very small area (sometimes primarily to inform on the depth to archaeological deposits as opposed to geological investigation), only those boreholes useful for informing on the Holocene geological history of the delta were included.

¹⁸Tristant et al. (2011)

¹⁹Tristant (2006); Tristant and De Dapper (2009); Tristant et al. (2008, 2007)

²⁰Hamdan (2003)

²¹Pawlikowski (2006); Pawlikowski and Wasilewski (2012)

TABLE 2: Stratified dates from the fluvial zone of the Nile Delta. All radiocarbon dates have been recalibrated according to IntCal13 (Reimer et al., 2013). “Bilqas 1 / Bilqas 2” indicates the contact between the units; Bilqas 1/2 indicates undivided deposits. A small number of dates within this table were excluded from being used to represent an aggradation history for the Nile Delta floodplain as it was thought they did not provide representative fluvial floodplain aggradation rates, if for example they were not located within stratified floodplain facies of the Bilqas Formation or were from very organic-rich sedimentary deposits which data suggest have undergone substantial compaction. These are marked with a “*”.

Core	Zone	Location	Depth (m)	Type	^{14}C BP	cal BP	Unit	Reference
S4	NC	31.515E, 31.2283N	0.95 – 1.45	^{14}C	2990 ± 90	3382 – 2924	Bilqas 1	Stanley et al. (1996)
S4	NC	31.515E, 31.2283N	2.45 – 2.95	^{14}C	2150 ± 100	2348 – 1901	Bilqas 1	Stanley et al. (1996)
S4	NC	31.515E, 31.2283N	5.25 – 5.75	^{14}C	4080 ± 130	4872 – 4159	Bilqas 1	Stanley et al. (1996)
S4	NC	31.515E, 31.2283N	7.75 – 8.25	^{14}C	5330 ± 120	6396 – 5772	Bilqas 2	Stanley et al. (1996)
S4	NC	31.515E, 31.2283N	9.85 – 10.35	^{14}C	5510 ± 150	6637 – 5946	Bilqas 2	Stanley et al. (1996)
S4	NC	31.515E, 31.2283N	11.95 – 12.45	^{14}C	6880 ± 100	7931 – 7575	Bilqas 2	Stanley et al. (1996)
S4	NC	31.515E, 31.2283N	13.75 – 14.25	^{14}C	7020 ± 120	8148 – 7612	Bilqas 2	Stanley et al. (1996)
S32	NC	31.4083E, 31.28N	7.25 – 7.75	^{14}C	5880 ± 170	7158 – 6323	Bilqas 1 / Bilqas 2	Stanley et al. (1996)
S32	NC	31.4083E, 31.28N	11.65 – 12.15	^{14}C	7100 ± 130	8177 – 7677	Bilqas 2	Stanley et al. (1996)
S37	NC	31.28E, 31.37N	4.35 – 4.85	^{14}C	3260 ± 80	3692 – 3272	Bilqas 1	Stanley et al. (1996)
S37	NC	31.28E, 31.37N	12.55 – 13.05	^{14}C	6870 ± 170	8009 – 7435	Bilqas 2	Stanley et al. (1996)
S38	NC	31.1733E, 31.4217N	12.55 – 13.05	^{14}C	7240 ± 90	8302 – 7870	Bilqas 2	Stanley et al. (1996)
S38	NC	31.1733E, 31.4217N	13.45 – 13.95	^{14}C	7210 ± 130	8330 – 7789	Bilqas 2	Stanley et al. (1996)
S39	NC	31.0733E, 31.42N	1.85 – 2.35	^{14}C	3840 ± 100	4521 – 3972	Bilqas 1/2	Stanley et al. (1996)
S39	NC	31.0733E, 31.42N	2.75 – 3.25	^{14}C	4540 ± 290	5904 – 4440	Bilqas 1/2	Stanley et al. (1996)
S44*	NC	30.9917E, 31.4367N	0.55 – 1.05	^{14}C	2570 ± 70	2840 – 2379	Bilqas 1	Stanley et al. (1996)
S44*	NC	30.9917E, 31.4367N	2.75 – 3.25	^{14}C	4870 ± 80	5877 – 5330	Bilqas 1	Stanley et al. (1996)
S44*	NC	30.9917E, 31.4367N	3.85 – 4.35	^{14}C	3980 ± 80	4807 – 4159	Bilqas 1 / Bilqas 2	Stanley et al. (1996)
S44*	NC	30.9917E, 31.4367N	4.95 – 5.45	^{14}C	4870 ± 80	5877 – 5330	Bilqas 2	Stanley et al. (1996)
S44*	NC	30.9917E, 31.4367N	7.35 – 7.85	^{14}C	3260 ± 90	3702 – 3252	Bilqas 2	Stanley et al. (1996)
S44*	NC	30.9917E, 31.4367N	10.25 – 10.75	^{14}C	6370 ± 180	7590 – 6857	Bilqas 2	Stanley et al. (1996)
S44*	NC	30.9917E, 31.4367N	1.5 – 2.5	Pottery	X	2273 – 1980	Bilqas 1	Warne and Stanley (1993)
S44*	NC	30.9917E, 31.4367N	4 – 5	Pottery	X	2614 – 2273	Bilqas 2	Warne and Stanley (1993)
S44*	NC	30.9917E, 31.4367N	9 – 10	Pottery	X	3600 – 3500	Bilqas 2	Warne and Stanley (1993)
S5	NE	31.6583E, 31.1933N	2.05 – 2.55	^{14}C	1450 ± 80	1534 – 1186	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S5	NE	31.6583E, 31.1933N	4.75 – 5.25	^{14}C	2450 ± 80	2730 – 2350	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S6	NE	31.71E, 31.1083N	1.75 – 2.25	^{14}C	1910 ± 70	2033 – 1631	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S6	NE	31.71E, 31.1083N	5.55 – 6.05	^{14}C	3750 ± 60	4349 – 3921	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S7*	NE	31.8717E, 31.13N	1.25 – 1.75	^{14}C	2340 ± 90	2707 – 2152	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S7*	NE	31.8717E, 31.13N	1.75 – 2.25	^{14}C	4230 ± 100	5044 – 4444	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S7*	NE	31.8717E, 31.13N	2.45 – 2.95	^{14}C	3805 ± 40	4404 – 4083	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S7*	NE	31.8717E, 31.13N	3.25 – 3.75	^{14}C	2110 ± 100	2332 – 1885	Bilqas 1/2 over Coastal	Stanley et al. (1996)

TABLE 2: Continued from previous page

Core	Zone	Location	Depth (m)	Type	^{14}C BP	cal BP	Unit	Reference
S7*	NE	31.8717E, 31.13N	4.75 – 5.25	^{14}C	6300 ± 100	7425 – 6979	Bilqas 1/2 over Coastal	Stanley et al. (1996)
S9	NE	31.8783E, 30.9783N	2.55 – 3.05	^{14}C	3740 ± 150	4521 – 3697	Bilqas 2	Stanley et al. (1996)
S9	NE	31.8783E, 30.9783N	3.85 – 4.35	^{14}C	5140 ± 80	6175 – 5662	Bilqas 2	Stanley et al. (1996)
S23	NE	32.2533E, 30.83N	1.21 – 1.71	^{14}C	2490 ± 80	2740 – 2363	Bilqas 1/2 over MG	Stanley et al. (1996)
S24	NE	32.1717E, 30.8517N	0.6 – 1.1	^{14}C	4130 ± 180	5276 – 4150	Bilqas 1/2 over MG	Stanley et al. (1996)
S26	NE	32.03E, 30.9067N	1.13 – 1.63	^{14}C	2500 ± 170	2960 – 2148	Bilqas 1/2 over MG	Stanley et al. (1996)
S26	NE	32.03E, 30.9067N	2.16 – 2.66	^{14}C	2820 ± 120	3324 – 2743	Bilqas 1/2 over MG	Stanley et al. (1996)
S26	NE	32.03E, 30.9067N	5.29 – 5.79	^{14}C	4370 ± 170	5465 – 4524	Bilqas 1/2 over MG	Stanley et al. (1996)
S26	NE	32.03E, 30.9067N	5.98 – 6.48	^{14}C	4210 ± 90	4972 – 4446	Bilqas 1/2 over MG	Stanley et al. (1996)
D21	NE	32.025E, 30.9019N	5.5 – 6.5	^{14}C	5045 ± 125	6176 – 5487	Bilqas 2	Andres and Wunderlich (1992)
D71	NE	32.03E, 30.9132N	6.5 – 7.25	^{14}C	3975 ± 80	4805 – 4158	Bilqas 2	Andres and Wunderlich (1992)
D5	NE	32.0314E, 30.9135N	8.68 – 9.68	^{14}C	6900 ± 200	8160 – 7431	Bilqas 2	Andres and Wunderlich (1991)
D4	NE	32.0386E, 30.916N	5 – 6	^{14}C	4095 ± 30	4811 – 4451	Bilqas 2	Andres and Wunderlich (1991)
D8	NE	32.0435E, 30.917N	4.92 – 5.92	^{14}C	4870 ± 95	5891 – 5327	Bilqas 2	Andres and Wunderlich (1991)
D22*	NE	32.0248E, 30.9033N	3.15 – 3.85	^{14}C	3175 ± 215	3921 – 2854	Bilqas 1 / Bilqas 2 ²²	Andres and Wunderlich (1992)
D22*	NE	32.0248E, 30.9033N	6.15 – 6.85	^{14}C	3215 ± 150	3836 – 3062	Bilqas 1 / Bilqas 2 ²²	Andres and Wunderlich (1992)
D46*	NE	32.0279E, 30.9125N	7 – 7.6	^{14}C	5690 ± 130	6791 – 6274	Geziracover?	Andres and Wunderlich (1992)
S54	NW	30.7917E, 31.3267N	4.35 – 4.85	^{14}C	3080 ± 70	3447 – 3077	Bilqas 1 / Bilqas 2	Stanley et al. (1996)
S55	NW	30.6717E, 31.315N	3.11 – 3.61	^{14}C	2420 ± 110	2752 – 2180	Bilqas 1	Stanley et al. (1996)
S55	NW	30.6717E, 31.315N	5.32 – 5.82	^{14}C	3400 ± 100	3899 – 3404	Bilqas 1 / Bilqas 2	Stanley et al. (1996)
S55	NW	30.6717E, 31.315N	6.77 – 7.27	^{14}C	4170 ± 90	4869 – 4437	Bilqas 2	Stanley et al. (1996)
S66	NW	30.452E, 31.266N	6.75 – 7.25	^{14}C	4020 ± 100	4825 – 4241	Bilqas 1	Stanley et al. (1996)
S66	NW	30.452E, 31.266N	9.25 – 9.75	^{14}C	3950 ± 70	4780 – 4155	Bilqas 2	Stanley et al. (1996)
P115	NW	30.7281E, 31.3113N	4.5 – 4.6	^{14}C	4755 ± 130	5844 – 5052	Bilqas 1/2	Wunderlich (1989) ²³
P115	NW	30.7281E, 31.3113N	5.65 – 5.8	^{14}C	4755 ± 75	5604 – 5317	Bilqas 2	Wunderlich (1989)
P115	NW	30.7281E, 31.3113N	6.35 – 6.5	^{14}C	6150 ± 55	7235 – 6890	Bilqas 2	Wunderlich (1989)
P115	NW	30.7281E, 31.3113N	6.65 – 6.7	^{14}C	6800 ± 200	8021 – 7311	Bilqas 2	Wunderlich (1989)
P87	NW	30.7284E, 31.2203N	7.35 – 7.45	^{14}C	5970 ± 180	6891 – 6310	Bilqas 2	Wunderlich (1989)
P02*	NW	30.7305E, 31.2749N	7.55 – 7.75	^{14}C	4595 ± 55	5467 – 5052	Bilqas 2	Wunderlich (1989)
P04*	NW	30.7332E, 31.2749N	8.7 – 9	^{14}C	4600 ± 45	5306 – 4979	Bilqas 2	Wunderlich (1989)
P24	NW	30.7351E, 31.2734N	7.3 – 7.55	^{14}C	4510 ± 90	5447 – 4870	Bilqas 2	Wunderlich (1989)
P24	NW	30.7351E, 31.2734N	8.35 – 8.55	^{14}C	6140 ± 125	6200 – 5610	Bilqas 2	Wunderlich (1989)
P08*	NW	30.7259E, 31.2646N	8 – 8.4	^{14}C	6135 ± 75	7244 – 6800	Bilqas 2	Wunderlich (1989)
P51*	NW	30.7033E, 31.2593N	7.2 – 7.4	^{14}C	5840 ± 120	6954 – 6353	Bilqas 2	Wunderlich (1989)

²²Two radiocarbon dates come from within channel fill deposits contemporary with the transition from Bilqas 2 to Bilqas 1.²³The small number of dates collected on carbonate nodules in this paper were ignored due to concerns over reservoir effects.

TABLE 2: Continued from previous page

Core	Zone	Location	Depth (m)	Type	^{14}C BP	cal BP	Unit	Reference
P52	NW	30.69E, 31.2484N	6.95 – 7.15	^{14}C	5720 ± 135	6851 – 6278	Bilqas 2	Wunderlich (1989)
P18	NW	30.7225E, 31.2452N	6.75 – 7.2	^{14}C	5870 ± 70	6877 – 6497	Bilqas 2	Wunderlich (1989)
P12	NW	30.7457E, 31.2492N	6.3 – 6.9	^{14}C	6810 ± 140	6945 – 6310	Bilqas 2	Wunderlich (1989)
P13	NW	30.724E, 31.2343N	6.95 – 7.25	^{14}C	5610 ± 45	6477 – 6303	Bilqas 2	Wunderlich (1989)
P27	NW	30.7526E, 31.2267N	6.7 – 6.85	^{14}C	5700 ± 175	6952 – 6031	Bilqas 2	Wunderlich (1989)
P39	NW	30.7747E, 31.2218N	6.9 – 7	^{14}C	5930 ± 120	7155 – 6469	Bilqas 2	Wunderlich (1989)
P37	NW	30.7971E, 31.2212N	4.15 – 4.55	^{14}C	2765 ± 80	1824 – 1548	Bilqas 1	Wunderlich (1989)
P37	NW	30.7971E, 31.2212N	5.15 – 5.25	^{14}C	4490 ± 150	5582 – 4826	Bilqas 2	Wunderlich (1989)
P35	NW	30.7988E, 31.2128N	4.8 – 5.15	^{14}C	4540 ± 150	5582 – 4854	Bilqas 1	Wunderlich (1989)
P34	NW	30.8302E, 31.2203N	5.85 – 6	^{14}C	4250 ± 185	5437 – 4295	Bilqas 2	Wunderlich (1989)
P121	NW	30.7103E, 31.1725N	2.45 – 3.85	Pottery	X	5750 – 5150	Bilqas 1	Wunderlich (1993)
KA/KW	NW	30.4465E, 31.1617N	3.5 – 3.9	Pottery	X	2550 – 1980	Bilqas 1	Pennington (unpublished) ²⁴
Tell Mutubis	NW	30.5478E, 31.2831N	2 – 2.5	Pottery	X	1980 – 1250	Bilqas 1	Pennington (unpublished) ²⁵
S87	C	31.0317E, 30.74N	0.36 – 0.86	^{14}C	1720 ± 80	1823 – 1414	Bilqas 1/2	Stanley et al. (1996)
S87	C	31.0317E, 30.74N	8.6 – 9.1	^{14}C	7030 ± 130	8155 – 7615	Bilqas 1/2	Stanley et al. (1996)
AUSE ²⁶	E	31.669E, 30.665N ²⁶	3.07 – 3.27	^{14}C	4079 ²⁷	4845 – 4297	Bilqas 1	de Wit (1993)
AUSE ²⁶	E	31.669E, 30.665N ²⁶	3.07 – 3.27	^{14}C	4421 ²⁷	5312 – 4838	Bilqas 1	de Wit (1993)
AUSE ²⁶	E	31.669E, 30.665N ²⁶	4.5 – 4.7	^{14}C	4421 ²⁷	6279 – 5755	Bilqas 1	de Wit (1993)
AUSE ^{*26}	E	31.669E, 30.665N ²⁶	?? ²⁸	^{14}C	4421 ²⁷	7248 – 6751	Bilqas 2	de Wit (1993)
AV02AV54*	E	31.824E, 30.7896N	3.9 – 4.1	OSL	X	8690 – 7030	Geziracover	Tronchère et al. (2012) ²⁹
AV02AV54*	E	31.824E, 30.7896N	4.9 – 5.1	OSL	X	13140 – 10940	Mit Ghamr	Tronchère et al. (2012)
AV02AV54*	E	31.824E, 30.7896N	6.4 – 6.6	OSL	X	16740 – 13540	Mit Ghamr	Tronchère et al. (2012)
TIA	E	31.83E, 30.8494N	3.6 – 4.6	Pottery	X	5150 – 4950	Bilqas 1/2	van den Brink (1992)
KHD	E	31.8483E, 30.528N	3 – 4	Pottery	X	5250 – 4840	Bilqas 1/2	Hamdan (2003)
S86	W	30.7967E, 30.855N	1.28 – 1.78	^{14}C	1690 ± 80	1811 – 1409	Bilqas 1	Stanley et al. (1996)
S86	W	30.7967E, 30.855N	7.38 – 7.88	^{14}C	4910 ± 100	5906 – 5334	Bilqas 1	Stanley et al. (1996)
S86	W	30.7967E, 30.855N	16.53 – 17.03	^{14}C	6430 ± 110	7571 – 7156	Bilqas 2	Stanley et al. (1996)
Sais	W	30.7683E, 30.965N	6.5 – 10	Pottery	X	7450 – 5850	Bilqas 2	Wilson (2006b) ³⁰

²⁴Archaeological levels contemporary with early settlement at Kom al-Ahmer persist in the nearby hinterland at 3.5-3.9m below the ground surface.²⁵Archaeological levels contemporary with settlement at Tell Mutubis persist in the nearby hinterland at 2.0-2.5m below the ground surface.²⁶The AUSE radiocarbon dates come variously from cores AUSE1352, AUSE1351, AUSE1440, AUSE1453, AUSE1452.²⁷The AUSE radiocarbon dates were presented by de Wit (1993) as calibrated according to Stuiver and Kra (1986) but with no error estimates; for modern calibrated estimates these were uncalibrated using Oxcal, then recalibrated to IntCal13 with a nominal error introduced of $\pm 100^{14}\text{C}$ yr.²⁸No depth was ever given for this date.²⁹Younger dates in this paper were not included as they were from anthropogenically modified contexts.³⁰Neolithic pottery layers were consistently found at these depths.

TABLE 2: Continued from previous page

Core	Zone	Location	Depth (m)	Type	¹⁴ C BP	cal BP	Unit	Reference
MUWDS	W	30.563E, 30.969N	3 – 4	Pottery	X	2250 – 1950	Bilqas 1/2	Wilson (2007) ³¹
Kom Geif	W	30.595E, 30.9N	4.9 – 5.6	Pottery	X	2600 – 2280	Bilqas 1	Pennington (unpublished) ³²

³¹Cores Jinbawy-2 and Jinbawy-3 found Ptolemaic pottery around 3m deep; also at Dinshal around 3-4m deep.

³²Archaeological levels contemporary with Late Period Naukratis persist in the nearby hinterland at 4.9-5.6m below the ground surface.

DATUM CONVERSIONS:

In order to convert the elevations of cores whose heights were originally presented as referenced to EGM008 or EGM96 into the SOE datum a conversion was applied to each point. The variable geoid heights of EGM2008 and EGM96 over the WGS-84 (NAD-83) ellipsoid were downloaded from NASA (2008; 1998), while a proxy model for the height of the SOE datum over the same ellipsoid (Fig. 1) was created from the EGM2008 geoid model using a conversion derived by Dawod et al. (2010), which adjusted the EGM2008 global geoid model according to equation 1. This “adjusted” geoid model N_{2008}^1 performed well in the delta region, with a standard deviation of its residual in the delta area against the “true” geoid (approximated by the SOE datum) that varied by approximately 0.6m.

$$N_{2008}^1 = 1.271413252 + 0.897054105 \times EGM2008 \quad (1)$$

INTERPOLATION OF GEOLOGICAL SURFACES – TECHNICAL DETAILS:

The modelling of geological surfaces was carried out within Rockworks 15, a standard mining industry software package produced by Rockware (2008), using a Kriging algorithm. This Kriging process assumed the semivariogram was gaussian with nugget, used an X–Y–Z node spacing of 664m–664m–0.5m, a spoke spacing of 45°, distance increment of 664m, eight neighbours, a maximum search radius of 8km (the average range of the best-fit semivariograms for the data across the whole delta), as well as high fidelity, densify and decluster tools.

This Kriging process does not use the data to its full extent, in that it necessarily ignores all data from a borehole in the interpolation of a particular unit if that unit is not encountered in the borehole. For example, if a model was run to create the top surface of the Mit Ghamr Formation it would entirely ignore a borehole 8m deep that only penetrated sediments of the Bilqas Formation, even though this borehole contains relevant information, constraining the top of the Mit Ghamr formation at this point to a depth *below* 8m. In order to account for this, second models for each interpolated surface (“Surfaces of Maximum Elevation”) were also created by running the same Kriging algorithm but with adjusted borehole data. For this adjusted model, each borehole that did not encounter the Mit Ghamr Formation had its record modified such that the Mit Ghamr Formation was placed with a thickness of 0m at the base of the hole. This produces a a minimum depth (maximum elevation) estimate of the full stratigraphy which would have been encountered had the borehole continued deeper and not terminated within the higher units. Final surfaces were created from a hybrid of the original surface and the surface of maximum elevation: the original surface was used in places where the “Surface of Maximum Elevation” was higher than the original; the “Surface of Maximum Elevation” was used in places where it was lower than the original. This produced a best-estimate maximum elevation model for each surface.

ABBREVIATIONS WITHIN SUPPLEMENTARY INFORMATION:

AUSE: Amsterdam University Survey Expedition to the Nile Delta

BRS: Buto Regional Survey

KA/KW: Kom al-Ahmer/Kom Wasit

KK/TS: Kom el-Khilgan/Tell es-Samara

KHD: Kafr Hassan Dawood

MAO: Minshat Abu Omar

MAS: Minufiyeh Archaeological Survey

MEDIBA: Mediterranean Basin project of the Smithsonian Institution

MG: Mit Ghamr

MUWDS: Mansoura University Western Delta Survey

SOE: Survey of Egypt

TIA: Tell Ibrahim Awad

WDLP: Western Delta Landscape Project

WDRS: West Nile Delta Regional Survey

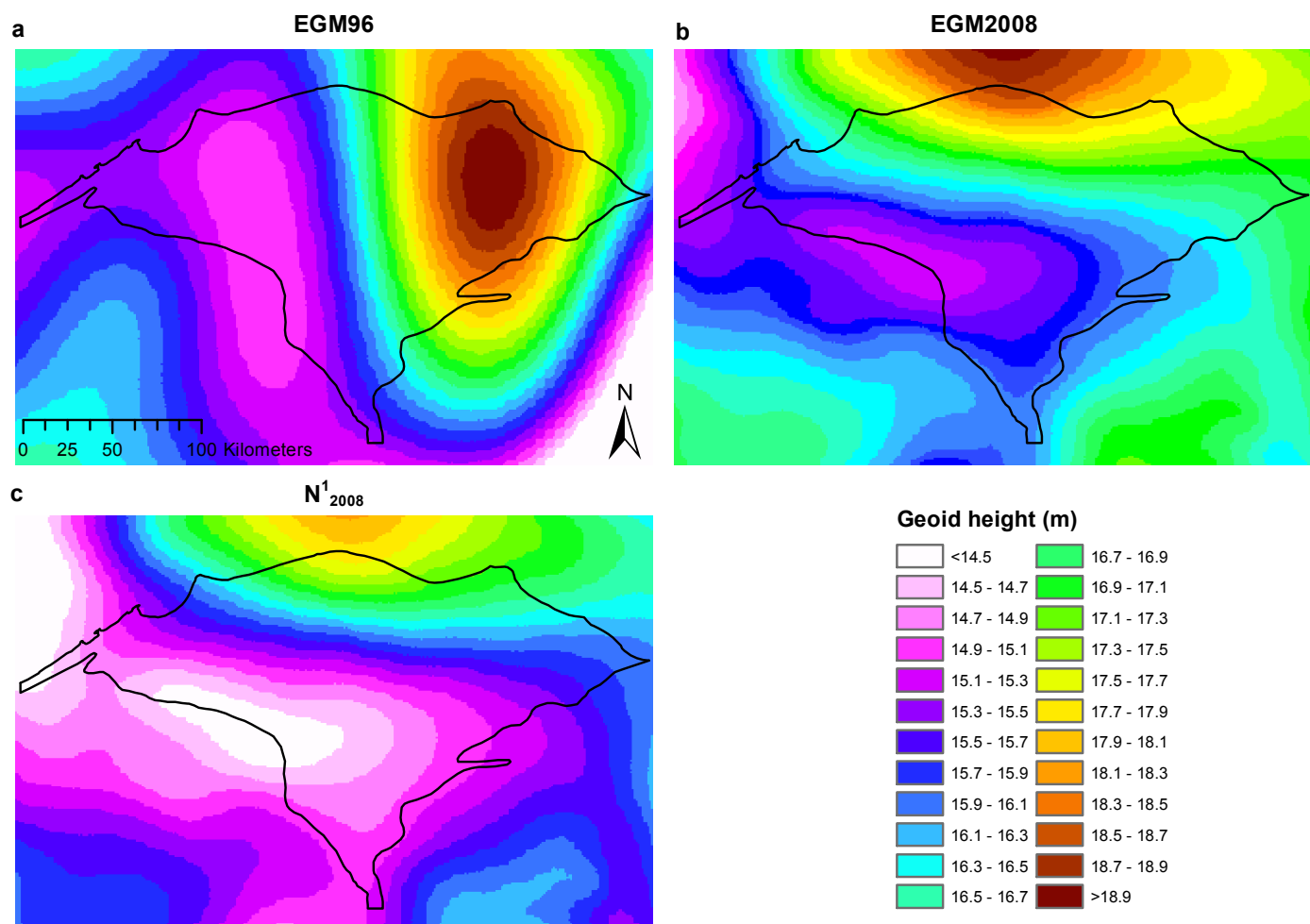


FIGURE 1: Variability in geoid models across the Nile Delta, expressed relative to the WGS-84 ellipsoid. a) EGM96; b) EGM2008; c) the proxy Survey of Egypt datum defined by Dawod et al. (2010), and used within the database.